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HARVARD OBSERVATORY MONOGRAPHS

No. 5

Variable Stars

BY

CECILIA PAYNE-GAPOSCHKIN

AND

SERGEI GAPOSCHKIN

Awake, awake! The world is young,
For all its weary years of thought:
The starkest fights must still be fought,
The most surprising songs be sung.

James Elroy Flecker

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To

HENRY NORRIS RUSSELL

INTRODUCTION

There is no need, in a modern book on variable stars, to give a review of the historical development of the subject; that has been done thoroughly by Hagen and Stein in their book, "Die Veränderlichen Sterne." We shall only mention the broader features of recent developments. In the interval of more than three centuries, since the discovery of Tycho Brahe's nova in 1572, the study of variable stars has been for the most part neglected. Only during the last two or three decades has it become one of the important branches of astronomy. At least one third of all astronomers are now concerned with variables, and the result has been an almost unparalleled growth, both of knowledge and of ideas.

The first important researches on variable stars were carried out in Europe. Whereas in France, during the past century, the chief concern was the development of mathematical astronomy, the interest in Germany centered about astronomical instruments and observational data, and it was therefore natural that the first systematic observers of variable stars should be Germans. In recent years the center of gravity of the study of variable stars has shifted from Europe to the United States, and, still more recently, toward Russia.

The book now offered to the reader is concerned with our present observational knowledge of variable stars. The field that we have attempted to cover is wide, since it embraces all known types of variable stars, including some that lie outside the galactic system. It is scarcely possible to come to an understanding of variable stars without surveying them as a group. Nevertheless the modern tendency has been in the direction of segregation into types that are considered and interpreted independently. This tendency, dangerous enough for the observer and classifier of information, is fatal to the theoretical worker, for it robs him of the opportunity to grasp the broad implications of the phenomenon in which he is interested—a phenomenon that may in itself seem simple, until its antecedents are realized. Instead, therefore, of dissecting the domain of variable stars, we have attempted to build the various parts into a coherent whole.

No claim to originality can be made for this view. It is shown in the relevant sections of the "Astronomy" of Russell, Dugan, and Stewart, in the Russian text-book: "Course of Astrophysics and Stellar Astronomy" (edited, and partly written, by Gerasimovič), in Vorontsov-Velyaminov's "New Stars and Galactic Nebulae," and in "Stellar Variability" by Parenago and Kukarkin; the three last books are unfortunately not accessible to readers unacquainted with Russian.

In each chapter of the present book we have attempted to give a general picture of the state of knowledge concerning the particular subject treated. Lists of the well-established members of the groups into which we have classified the variables form, in our opinion, an important part of the work. Excessive detail about any one object has been avoided, often with great regret; but an attempt has been made to give enough references to original work to enable the reader to trace the interesting details for himself.

In a comparatively small book like the present, it is nearly impossible to be bibliographically complete; but for variable stars this is the less regrettable as the "Geschichte und Literatur des Lichtwechsels von Veränderlichen Sternen" will be found to furnish complete bibliographies of individual stars. It is, moreover, natural that a book written at the Harvard Observatory, which has from the beginning been a center of research, of accumulation of data, and of thought, concerning variable stars, should contain many references to work that has been done here. If similar results, obtained elsewhere, are not always mentioned, the excuse has often been a desire for compactness. It is hoped that no lack of balance in fact or idea has resulted from this tendency; but if such be noted, it has crept in against our will. Few books written in large research institutions will be found to be free from a similar defect.

In our work we have been inspired by innumerable discussions with our colleagues. We are deeply indebted to Professor H. N. Russell, whose critical reading of the manuscript and invaluable comments have contributed more to the completed book than we can easily express. Especially are we indebted to Dr. Harlow Shapley for his continual help, both visible and invisible.

We hope that our attempt to depict the panorama of the variable stars will provoke and direct future investigations, and that the astronomer may find in it some help in orienting himself among the variables, which are appearing so fast that they bid fair to envelop him like a thickly growing forest, through which it will soon be too late to cut a path.

C. P.-G.
S. G.

1938

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A

INTRODUCTORY

CHAPTER I

VARIABLE STARS — A SURVEY

> O gloriose stelle, o lume pregno
> di gran virtu dal quale io riconosco
> tutto, qual che si sia, il mio ingegno . . .*
>
> Dante

The arrangement of the variable stars in coherent groups is one of the principal purposes of our treatise. Some of the groups are already recognized, others are now formed or defined for the first time, and yet others (previously used) have been rejected, by the absorption or redistribution of their members.

The reader (who, unlike the authors, has not surveyed the field before beginning on the book) will prefer to have a glimpse of the territory that he is about to cover, before he begins to survey the individual districts and to examine their features. The first chapter therefore contains a short summary and survey, which might more logically have been placed at the end of the book.

We have divided the variable stars into four great groups: geometric variables; intrinsic variables; cataclysmic variables; and extrinsic variables. The first chapter that deals with each group will be found to contain a more general description of the members of the group than has been attempted in the preliminary survey.

1. Types of Stellar Variability.—*Changes of brightness* are the most readily observed criteria of variability, but they are not necessarily the most significant features of the process, nor indeed are they invariably present—the spectrum variables, for

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* O glorious stars, O light impregnate with great virtue, from which I acknowledge all my genius, whatever it may be . . .

Charles Eliot Norton's translation

instance, may not vary in brightness. *Changes of position,* both tangential and radial, are of course to be referred to the true motion of the star, and variations of tangential motion, like those displayed by Sirius, have an evident dynamical interpretation; they may be found, associated with true variability, in Polaris. Some *changes of radial motion,* those of the true spectroscopic binaries, are likewise to be referred to the true motion of one or more stars.

But a second class of regular and periodic changes of radial velocity, not referable to the real motions of the stars concerned, is encountered in the Cepheids, the cluster type stars, and probably the long-period variables, all of which are now regarded as intrinsic variables. Such motions must be considered to reside principally in the outer layers, rather than in the star as a whole, and to possess some sort of radial symmetry; presumably they involve changes in the volume of the star, possibly also in its form. The velocity curves of intrinsic variables are not always distinguishable, without additional information, from those of the spectroscopic binaries.

A third class of variable radial velocities involves changes not unlike those just described, except that they are not periodic in character; many second-type supergiants, such as γ Cygni, display variations of this sort, variations which probably involve only the outer portions of the star, and may lack radial symmetry. A different kind of change of radial velocity, sudden, short-lived, and numerically much larger, is shown by the novae and the SS Cygni stars.

The last three types of variation of radial velocity mentioned are almost invariably associated with changes of brightness, of color, and of spectrum. They all appear to involve bodily motions of parts of the star, principally the outer layers. It appears that the more abrupt and large are the changes in radial velocity, the more superficial is the associated change in the star.

There is little or no convincing evidence of permanent changes in stars of any type during the interval over which they have been studied. The continual loss of radiated energy by all observable stars, and of matter by a few small classes of stars, such as the Wolf-Rayet objects and the P Cygni stars, must necessarily lead in time to fundamental changes. But such changes could not possibly have been detected within the two millenia over which observations of the naked-eye stars are available, when we consider the low accuracy of the early magnitudes. We can say little more than that the stars that were naked-eye objects two thousand years ago are naked-eye objects still, with roughly the same relative brightnesses. The exhaustive discussions of secular changes of brightness of the stars by Zinner and others[1] lead to quantities so small in comparison with their errors that they cannot be considered significant.

Fundamental changes in periodic variable stars should be shown by secular changes in their periods, which form much more delicate and easily observed criteria than the changes of brightness that should theoretically accompany them. For Cepheids and cluster-type variables a few true secular changes of period have been demonstrated; for long-period variables true changes of period, where they have been found, are rather uncommon.

Novae and R Coronae Borealis stars, of which the former, at least, change in mass with every outburst, appear to return within a few months or years to their pre-disturbance condition, at least in many respects. Thus even the most violently disturbed variables have furnished no definite evidence of permanent alteration.

Change of brightness is a restricted case of a far more extensive group of changes — the changes in the total amount and distribution in wave-length of the energy emitted by the star. Magnitudes in the visual, photographic, photovisual, red, infrared . . . systems represent the integration of the light received at the surface of the Earth and effective on the receiving apparatus, between definite limits of wave-length. Each of the systems mentioned includes but a narrow strip of the total spectral energy sent out by the star, and it is evident that the change of energy received within any one strip will be proportional to the total change of the energy emitted by the star as a whole only if this change of total energy is accomplished without a change in surface brightness. Roughly speaking, such a change could be produced only by an alteration in the surface area of the star without a change in the energy-distribution of the radiation—a condition certainly not fulfilled for any known type of variable star, though probably approached most nearly in the pre-maximum stages of novae.

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[1] Zinner, Phys. Zs., 31, 440, 1930; A.N., 237, 77, 1929; *Ibid.*, 238, 65, 1930; see Lundmark, Handb.d.Ap., 5, 356, 1932; *Ibid.*, 7, 479, 1936.

All changes of brightness in intrinsic variables (that is, all changes not produced geometrically by simple obscuration of one body by another) are therefore accompanied by changes of surface brightness and there is thus no one limited range of wave-length within which the integrated change of energy will always be proportional to the integrated change of total energy. If, moreover, the stars radiate approximately like black bodies, (or if their radiation differs systematically and continuously from black-body radiation), the relative change of energy within two separated ranges of wave-length will not be the same; therefore, changes of brightness must necessarily result in changes of color, as determined from spectrophotometric measures made over a variety of monochromatic wave-lengths, or from a comparison of the change in integrated energy between two separated pairs of wave-length limits. In fact, with the exception of the eclipsing stars (which are not intrinsic variables) and the novae and SS Cygni stars before maximum (where the data are regrettably meager), all variations of brightness are accompanied by observed changes of color.* A few reports of changes of color without evident changes of brightness, such as those for α Cygni and μ Centauri, seem to be well substantiated; but it is not certain that they involve changes in surface brightness.

The close connection of surface brightness with effective temperature makes it probable that all changes of the former will involve the phenomena associated with changes of the latter, and they are indeed invariably accompanied by changes in the line spectrum, which form a large part of the useful data concerning variable stars. The long-period variables and their relations, the Cepheids and the cluster-type stars, all of which presumably vary in volume, in surface area, and in surface brightness, display associated changes in total brightness, in color, and in spectral type (in addition to the changes of radial velocity, which we do not consider as constituting *in themselves* a variable spectrum).

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* The apparent exception of the long-period variables is not real; the changes of energy distribution, which accompany the changes in surface brightness, are masked by the effects of the band spectrum.

There are also a number of stars of exceptional interest, which have spectral variations that are more conspicuous than any other changes that they show. These stars are presumably surrounded by variable atmospheres, while their total volume below the atmosphere, their surface brightness, and their total radiation are not necessarily subject to variation. No hard-and-fast line can be drawn between the intrinsic variables and the spectrum variables; and many, if not all, of the latter will undoubtedly be found to vary in brightness when they are examined with the necessary precision. The largest group of spectrum variables comprises the Be stars, such as γ Cassiopeiae, φ Persei, μ Centauri, and Pleione; three of these stars are definitely variable in brightness, and the fourth has been held to vary in color. The class, which will be analyzed in a later chapter, also contains a number of apparently unrelated peculiar objects, such as υ Sagittarii.

In general it may safely be concluded that a variation of a star as a whole will be accompanied by variation of the atmosphere, but that atmospheres, especially those of stars of low surface gravity, may be subject to independent variations large enough to have a sensible effect on the spectrum. An extreme case of the independently varying atmosphere is presented by a star imbedded in free nebulosity; such objects comprise perhaps the most interesting of all spectrum variables and are treated in a later chapter. It is, however, possible that the varying atmosphere or nebular envelope always has some effect on the star that is embedded in it, so that even in this case the star will not vary in one particular only.

Changes of radial velocity and of color, such as occur for many intrinsic variables, are considered to be associated with changes of size, but the number of stars for which changes of size can be *directly* measured is limited to those objects of great enough angular diameter to be accessible to the interferometer. At present it cannot be said that such measures have achieved any more than a confirmation of the fact that real changes of diameter take place, at least for red giant stars.

2. General Classification of Variable Stars.—In the present book an attempt is made to arrange and discuss the variable stars in physically significant groups. The classification adopted has much in common with other systems, such as those of Pickering and Ludendorff, and it has also some features that they do not share. Two aims have been kept in mind: first, to define the classes with a minimum of ambiguity; second, to examine critically all adequately observed stars that have been assigned to a given class, in order to form lists of all the well-observed stars of a given kind. There has been, in the past, an excessive tendency to form small groups of uncertain affiliations, by assigning one star to a small class called after another star which it somewhat resembles. To quote an example, taken at random from Prager's Catalogue for 1936: TU Octantis is described as of XX Ophiuchi type; XX Ophiuchi is described as of R Coronae Borealis type; and R Coronae Borealis is described as "Irregular": evidently such classifications only introduce confusion, and it is desirable, as far as possible, to avoid all classes that are named after individual stars (which may on further analysis appear, like RV Tauri, not to be true members of the class that bears their name; or, like β Lyrae, to be one of the most abnormal of the stars in the class that has come to be called after them).

The classification that has been adopted for use in the present book is summarized in Table I, I; the definitions of the classes will be found in the chapters devoted to them.

The first group (geometrical variables) comprises stars whose variation of light can be interpreted, at least in its main outlines, in terms of the geometrical properties of the system. All eclipsing stars fall into this group, but some of them display additional effects that cannot be interpreted in geometrical terms. For example, ϵ Aurigae and W Serpentis have additional variations of brightness, apparently unconnected with the eclipse, and

TABLE I, I

CLASSIFICATION OF VARIABLE STARS

A. Geometrical Variables	B. The Great Sequence	C. Cataclysmic Variables	D. Nebular Variables
Eclipsing stars	Long-period variables	Novae	
Ellipsoidal stars	Semiregular variables	SS Cygni stars	
Obscured stars?	Cepheid variables	(R Coronae Borealis stars)	
	Cluster-type stars		
	(Irregular Red Variables)		

secondary effects are observed for many other eclipsing stars, as discussed in Chapter II. It has commonly been assumed that variable stars such as are found in the Orion nebula can be interpreted in terms of obscuration by nebular material. A discussion of these stars is given in Chapter XI.

The Great Sequence is the most natural group in the present classification, but a definition must be somewhat vague, for few stars will be found to satisfy all the criteria, although all the types mentioned are undoubtedly members of one group. The following five features are characteristic of most members of the

TABLE I, II

CRITERIA FOR THE GREAT SEQUENCE

Criterion:	a	b	c	d	e
Long-period variables	Yes	Yes	Yes	Yes	Yes†
Cepheid variables	Yes	Yes*	Yes	Yes	Yes
Cluster-type variables	Yes	Yes*	Yes	Yes	Yes†
Semi-regular variables:					
R Sagittae	Yes	Yes	At intervals	Yes	Yes?
RV Tauri	Yes	Yes	No	Yes	Yes?
UU Herculis	Sometimes	?	At intervals	Yes	?
DF Cygni	Yes‡	Yes	Yes‡	Yes	Yes?
W Cygni	Roughly	Yes	No	Yes	Yes?

* Sometimes equally steep.

† The relation does not hold within the group.

‡ Two periods; the shorter one conforms to the period-spectrum relation.

Great Sequence: (a) a definite periodicity is present; (b) the light curve is never steeper in decline than in rise; (c) the light curve repeats itself; (d) spectrum, radial velocity, and color vary continuously throughout the period; (e) the stars follow a period-luminosity and period-spectrum relation. The closeness with which some members of the Great Sequence conform to these five criteria is illustrated in Table I, II.

It is of interest to note that many stars, especially of the semi-regular group, do not conform to all the criteria. Nevertheless we regard them as true members of the Great Sequence, because they show many of its features. The next table, containing the results of the same criteria applied to Group C (the cataclysmic variables), shows that, despite a few points in common, these stars differ widely from the Great Sequence.

TABLE I, III

GREAT SEQUENCE CRITERIA APPLIED TO THE CATACLYSMIC VARIABLES

Criterion:	a	b	c	d	e
Novae	No?	Yes	No	No†	No
SS Cygni stars	Yes	No	Roughly	No	No
R Coronae Borealis stars	No	No	No	No	No

† Continuous irregular variation of brightness outside, and independently of, the outburst is observed for some novae, and is perhaps a common feature.

A comparison of Tables I, II and I, III shows that no one criterion can ever be trusted invariably to discriminate between the members of the two groups; rather it should be concluded that Great Sequence stars are preponderantly positive to the criteria given, cataclysmic variables preponderantly negative. This is not to be taken to imply that there is no real distinction between the two groups; we consider that criterion (d), emphasizing the continuous variation of members of the Great Sequence, is the most important, and points to a fundamental difference between the processes taking place in the members of the two groups.

It should be emphasized that in every group there will be found some individuals that do not conform to all the criteria for that group. Furthermore it will sometimes be found that individuals that display all the characteristics of one group of variables may also have features in common with quite a different group. Such problematical variables will be discussed in their place.

3. Lists of Variable Stars.—The literature of variable stars has grown to unwieldy proportions during the last ten years, so that it is difficult for a theoretical worker to obtain a representative survey. Much of the published work, especially in earlier years, consisted of lists of newly discovered variables. Modern discovery announcements tend to include an indication of type of variability, and (better) accurate elements. A second, even larger branch of the literature describes detailed observations of stars already known to vary. Lastly, there are a number of more or less disconnected attempts to account theoretically for certain phases of stellar variability, but only few general attacks on the theory of the whole subject. The two first phases of the work are the province of this book. References to the third may be found in various chapters.

Extensive searches for variable stars have from the first been among the foremost photographic problems of the Harvard Observatory. The major contributors to the modern discovery of galactic variables have been Hamburg, Harvard, Johannesburg, Leiden, Moscow, Mount Wilson, Sonneberg, and Yerkes. The Astronomische Gesellschaft has for 27 years performed the valuable service of supervising the publication of an annual list of galactic variables, the "Katalog und Ephemeriden Veränderlicher Sterne" (Kleine Veröffentlichungen d. Berlin-Babelsberg). This catalogue contains the positions and elements for all published galactic variables that fulfill the requirements of the committee appointed by the Astronomische Gesellschaft: there must be definite evidence of variability; the brightness must be reliably determined; an accurate position must be given; and the type of light variation must be known (that the period is "short" is insufficient information).

A variable star that satisfies the criteria of the Committee receives a specific designation.[2] The one in use hitherto assigns letters to the variable stars in a constellation, in order of discovery, as follows: R, S, .. Z, RR, RS, ... RZ, SS, ST, ..., TT, ..., UU, ..., ..., AA, ..., QQ, ..., QZ ,V335, V336, ... A few variable stars, such as β Persei, receive no such designations, having entered the literature before the system was devised. A few designations, such as VY Geminorum, are omitted from the catalogue of variable stars, as the stars concerned have been shown not to be variable. By an unfortunate inconsistency some novae, such as Nova Pictoris, receive designations (e.g., RR Pictoris) in the usual system; for others a special notation is used. The boundaries of the constellations to which the stars are assigned have been fixed by a committee of the International Astronomical Union.[3]

Other systems of naming variable stars have been devised, notably one based on position for equinox 1900, long used at Harvard Observatory: for instance, UV Persei (2^h $3^m.3$, $+56°$ $43'$) is designated 020356; if the star is in southern declination the designation is underlined in writing or typing, italicized in print. If, because of closeness of position, more than one variable received a given designation, they were originally distinguished by small letters. This system, like all others, becomes unwieldy when many variables are known in a small area of the sky, and in the present book the numerical designation alone is used as a convenient and compact indication of approximate position.

The naming of variable stars is not a matter that should be allowed to consume much time or thought. If one unambiguous system is in general use for the variables known at present, there is no reason for abandoning it because it may be clumsy when applied to future discoveries. A classification, or a system of naming with a classificatory significance, must be abandoned if advancing knowledge shows it to be ill-founded. But the naming of variable stars is merely a convenience; no useful purpose would be served by making it consistent, and an enormous, valueless labor would be entailed by adopting a new system for all variable stars.

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[2] Published periodically in the *Astronomische Nachrichten* under the designation "Benennung von Veränderlichen Sternen."

[3] Délimitation Scientifique des Constellations, 1935.

A time will soon come for galactic variables, as it has come already for the variables in globular clusters, Magellanic Clouds, and extragalactic nebulae, when there will be no attempt to assign names; the variables will be identified from marked charts. Without this expedient it is not possible even now to identify some faint variable stars in Corona Austrina, Sagittarius, Scorpio, Norma, Triangulum Australe, and other constellations where intensive searches have been made. It is likely (because of the modern discoveries of faint galactic variables), that the "Katalog und Ephemeriden Veränderlicher Sterne" will in a few years assume such proportions that some further limitation will have to be placed upon the stars that shall be included. Probably a complete recasting of the present method of cataloguing known variable stars would be in the interests of convenience and economy.

The variable stars that satisfy the criteria mentioned above are included in the "Katalog und Ephemeriden." The best elements available (in the opinion of the compiler) are given for each star; occasionally these elements have not been published, though the variable itself must have been published to enter the catalogue. Clearly in a compilation of this kind there can be no pretense to uniformity. Nor can the compiler be considered to endorse the elements given; he merely indicates that they have been published somewhere, with enough corroborative detail to satisfy the committee of their verisimilitude. Anyone who makes the catalogue a basis for statistical discussion must realize that the magnitude systems used for different stars differ widely, and may be greatly in error—published ranges for stars that are little observed are commonly too large, usually because the extreme observed magnitudes are used, rather than the extremes of the mean light curve. Moreover the periods first derived are not always the right ones, and not infrequently even the type of variability is wrongly assigned at first. Lastly, published positions differ in precision. Any statistical study based on the catalogue must make particularly cautious use of the magnitudes. There is no real substitute for turning to the original sources (though even here there is often considerable uncertainty as to the basis for the system of magnitudes), and some independent work is necessary to reduce them to a known basis.

There are several classes of variable stars that are not included in the "Katalog und Ephemeriden." The principal *galactic* variables that do not appear in the compilation are: (1) unpublished variables (such as exist in large numbers in the records of the Harvard, Leiden, and other observatories, chiefly awaiting completer data); (2) stars of undoubted variability, but possibly identical with variables already included (many examples may be found among the stars published by Innes at Johannesburg, and by Ross at Yerkes); (3) variable stars that do not fall in with the criteria mentioned above.

Suspected variables—stars which, though regarded as variable by their discoverers, do not satisfy the criteria of the Astronomische Gesellchaft—must be remembered as possibly of unusual interest, since the number and behavior of small-range variables are very important. Lists of suspected variables have been published by Zinner[4] and by Prager.[5] A complete manuscript list has long been maintained at the Harvard Observatory, containing the stars that have been published as variable, or possibly variable, but not admitted by the "Katalog und Ephemeriden."

A catalogue of photoelectrically observed stars, complete to 1930, is contained in the "Katalog Lichtelectrisch Gemessener Sterne"[6] of Güssow and Guthnick; it includes all the photoelectric variables known up to that time, with references to the literature. Ninety-nine variables are included, several of them being bright Cepheids, which have been the subject of special photoelectric investigations; these will, of course, also be found in the "Katalog und Ephemeriden."

The important and growing class of spectrum variables (stars which vary spectroscopically, but not obviously in brightness) has not yet been systematized or compiled. They fall into two

[4] Astr. Abh., 8, No. 1, 1929.
[5] Astr. Abh., 9, No. 3, 1934; 10, No. 1, 1937.
[6] Kl. Veröff., Ber.-Bab., 2, No. 8, 1930.

groups, not necessarily mutually exclusive: those whose spectral lines (bright or dark) vary in intensity; those whose spectral lines vary in wave-length. Chapter XI includes a partial list of these stars. They are probably all photoelectrically detectable variables.

A complete bibliography of the variables known in globular clusters, up to 1930, is given in Shapley's monograph on Star Clusters,[7] in particular in Chapter IV. Most of the variables in clusters can be found only from marked charts, and for many clusters these charts have never been published.

There are at present about 1346 variable stars known in the Large Magellanic Cloud,[8] and about 2000 in the Small Cloud.[9] Of these, the majority have been discovered at Harvard; a small number have been published by Innes. About a thousand of the variables in the Small Magellanic Cloud are at present unpublished at the Harvard Observatory.

Between two and three hundred variable stars have been discovered, chiefly at Mount Wilson, in extragalactic nebulae. The systems principally represented, for variable stars other than supernovae, are Messier 31, Messier 33, and N.G.C. 6822,[10] and I.C. 1613.[11] Except for the novae in Messier 31 no charts have been published.

4. Bibliographies for Variable Stars.—The most useful working bibliography of the variable stars is the "Geschichte und Literatur des Lichtwechsels der Veränderlichen Sterne." The first section, in three volumes issued in 1916 by Müller and Hartwig,[12] contained collected references to the literature previous to that date; the second section,[13] containing references from

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[7] Shapley, Star Clusters, Harv. Mon. No. 3, 1930.

[8] Shapley, H. A., 90, No. 1, 1933.

[9] H. A., 60, 105, 1908; unpublished Harvard material.

[10] Hubble, Mt. W. Contr. 304, 1925; *Ibid.*, 310, 1926; *Ibid.*, 376, 1929; The Realm of the Nebulae, p. 134, 141, 144, 1936.

[11] Baade, quoted by Hubble, The Realm of the Nebulae, 145, 1936. *See also*, Ann. Rep., Mt. W. Obs., 1934-35.

[12] Geschichte und Literatur der Veränderlichen Sterne, First Edition, compiled by Müller and Hartwig, 1920.

[13] Geschichte und Literatur der Veränderlichen Sterne, Second Edition, compiled by Prager, 1934, 1936, *in progress.*

1916 to 1935, is now in process of appearing (two volumes, Andromeda-Ophiuchus, have been issued by Prager, and a third will complete the series). Besides this, several observatories maintain general manuscript bibliographies.

5. Ephemerides and Observing Lists. *a. Eclipsing Stars.* —Predictions of the minima of selected eclipsing stars, designed for the information of observers, are issued annually from the Cracow Observatory.[14] Extensive critical tables, containing suggestions and guidance for the observers of eclipsing stars, have been issued by Dugan[15] ("A Finding List for Observers of Eclipsing Variables") and by Martinoff[16] ("Program of Investigation of Eclipsing Variables"). The eclipsing stars are unfortunately the only type of variable for which a critical list of stars, and of desirable studies to be made of them, has been published. The remaining lists are merely summaries of variable stars of known type, and predicted times of maximum or minimum.

b. Cluster-Type Stars.—The Tadjik Astronomical Observatory[17] issues an annual list of cluster-type stars, including epochs of maximum, periods (revised from year to year), and predicted elements for the coming year. Maxima for cluster-type stars were computed for a number of years at Carleton College, and were published in *Popular Astronomy.*

c. Long-Period Variables.—Predicted times of maxima and minima for a selected list of long-period variables are issued at frequent intervals by Campbell for the American Association of Variable Star Observers.[18] Mention should also be made of the lists of variables regarded as of especial interest, given by Nijland,[19] and by Campbell.[20]

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[14] Rocznik Astronomiczny Obserwatorjum Krakowskiego, 1922-37.

[15] Dugan, Princeton Contr., No. 15, 1934.

[16] Martinoff, Engelhardt Obs. Bul. No. 2, 1934; *Ibid.*, No. 5, 1935.

[17] Tadjik Obs., Catalogue and Ephemeris of Short Period Cepheids, 1935-37.

[18] A.A.V.S.O. Bul., 1931-37.

[19] Nijland, B.A.N. 197, 1930.

[20] Campbell, Rep. of I.A.U., 1938.

B

GEOMETRIC VARIABLES

CHAPTER II

ECLIPSING BINARIES

> The splendours of the firmament of time
>   May be eclipsed, but are extinguished not.
>
> Shelley

We include eclipsing stars among the other variables because in practical astronomical work there is no distinction between them. Our knowledge that they are not intrinsic variables is a consequence of our interpretation of the light curve and the velocity curve (although for many stars the latter is actually unobserved); but not infrequently a star, first regarded as an intrinsic variable, has been found to be an eclipsing star (for example, SX Cassiopeiae, U Gruis, RY Scuti, VV Cephei, and many W Ursae Majoris stars). A few stars, such as RU Centauri, have at first been thought to be eclipsing stars and have later been shown to belong to another class. In recent years there has been a tendency to treat eclipsing stars among double stars (they are discussed in that section of the Handbuch der Astrophysik, for example); but an astronomer working on eclipsing stars would never be called a double star observer.

In many respects the eclipsing stars furnish the standards in the astronomical inventory, for they are our most important direct source of information about the physical properties of the stars. We shall therefore give a detailed but short description of them.

6. Relation of Eclipsing Stars to Other Fields of Inquiry.—The most intimate connection shown by the eclipsing stars is with the double star problem, and through it, with the three-body problem, which has recently been solved by Brown, completely in so far as it concerns the eclipsing systems. But though the problem of double stars has been exhaustively studied, there are still a number of important unsolved problems among the eclipsing stars. For example, given the radii, masses, and distance between two components, it is required to deduce the form that will be assumed by each of the two stars, in the light of our modern knowledge of internal conditions.

The eclipsing stars are also closely related to problems of cosmogony, which is itself closely bound up with the double-star problem. Eclipsing stars furnish information as to the physical condition and possible development of the members of double star systems.

In the field of stellar atmospheres the eclipsing stars may furnish important information, not only from the study of the structure of a deep atmosphere as provided by ζ Aurigae and perhaps by VV Cephei, but also from bright-line spectra such as those of β Lyrae, W Serpentis, RY Scuti, and $-66°3307$. Much information is available concerning the relative surface brightness (visual or photographic) of stars of different spectral types. In the few cases where both linear dimensions and parallax are known, the absolute surface brightness can be found. This gives values of the radiation temperature which may be regarded as the best of all criteria for establishing the scale of stellar temperatures.

The other variable stars, such as those of the Great Sequence, have no very close connection with the eclipsing stars. It is not impossible, however, that eclipses must be invoked to interpret the light curves of some semi-regular variables; and some eclipsing stars have light curves that seem to require that one, at least, of the components is intrinsically variable.

7. **Discovery of Eclipsing Stars.**—The first definite discovery of an eclipsing star was made in 1667 by Montanari, and the star was the well known β Persei (Algol). By 1937 there were about sixteen hundred known stars assigned to the eclipsing group. One thousand are stars of known period and primary minimum; for six hundred the secondary minimum is known; three hundred and fifty are of known spectrum (bright component or total spectrum); for sixty-three, the spectra of both

components have been observed; for two hundred and seventy systems the photometric elements have been computed; for about sixty systems spectroscopic elements have been derived, and for thirty-five systems the absolute dimensions (mass, radius, and density) of the components are known.

8. **Definitions.**—All eclipsing stars are usually divided into two groups according to the nature of the light curve—Algol stars and β Lyrae stars. Algol stars are considered to be of constant brightness between the minima, while for β Lyrae stars the variation is continuous. A subclass of the β Lyrae stars has been formed to include all such stars with periods less than a day, and minima of almost equal depth—the so-called W Ursae Majoris stars. The three classes are named after three well-known stars that belong to them, but in some ways the names are unhappily chosen, for both Algol and β Lyrae, especially the latter, are somewhat abnormal and peculiar members of their classes. Roughly speaking, the W Ursae Majoris stars may be supposed to be dwarfs, with the highest density found among eclipsing stars; but there are also Algol stars of high density. Further, the light curves of the W Ursae Majoris stars, with their continuous variation, show that the components have high ellipticities; but the β Lyrae stars have ellipticities almost as large. In fact no hard-and-fast line can be drawn between the different classes of eclipsing stars. For practical and general orientation among the light curves there is no need to make more detailed classification than is now commonly used: Algol, β Lyrae and W Ursae Majoris.[*] We are indebted to Professor H. N. Russell for the suggestion which we give below:

1. Light curve between eclipses not conspicuously convex.	
(a) Evident total phase at primary minimum	U Cephei
(b) No evident total phase at primary minimum	Algol
2. Light curve between eclipses conspicuously convex upward.	
(a) Period greater than (12^h) Minima equal or unequal	β Lyrae
(b) Period less than (12^h) Minima nearly equal	W Ursae Majoris

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[*] The same conclusion has been reached by Mergentaler [Acta Astr., Ser. C., 3, 88, 1938].

9. **Physical Groups.**—From the standpoint of physical characteristics we may mention that there are several groups of eclipsing variables, whose properties do not quite coincide with those of the type stars. The eclipsing star ζ Aurigae (like VV Cephei, and probably ϵ Aurigae), for example, is a system in which the components are very different in size, surface brightness, and spectrum. Y Cygni represents, on the other hand, a system in which the equal components are of very early spectrum, of high surface brightness, and of high mass. The systems having density of the order of that of the sun may be represented by W Ursae Majoris for highly elliptical components, or by WZ Ophiuchi for non-elliptical components. The star β Lyrae or RY Scuti may represent the systems in which the peculiarities of spectrum probably indicate atmospheric abnormalities. Finally, such systems as RU Monocerotis can be suggested as representative of eclipsing binaries in which the eccentricity is very pronounced and for which the apsidal motion has been determined. The majority of the eclipsing binaries are intermediate between these physical groups. Indeed, the only purpose in mentioning these representatives was not to emphasize the classes, but to give indications of the variety of observed physical properties which are of general importance.

10. **The Relative Numbers.**—The relative numbers of Algol, β Lyrae, and W Ursae Majoris stars have remained more or less constant as the discoveries have progressed. For the three years, 1930, 1936, and 1937, the discoveries were in the ratio 22: 72: 6 for elliptical (β Lyrae + W Ursae Majoris): non-elliptical (Algol): unclassified. These numbers, corrected for probable effects of selection, would become 30: 60: 10. The number of non-elliptical stars is at least twice as great as the number of elliptical stars; this fact does not depend on selection; it has probably a real cosmogonical significance. Of course we do not include in these statistics the large number of probable eclipsing variables with very small ranges.

11. **Periods.**—Only about eight per cent of the known eclipsing stars have periods greater than ten days; this percent-

age has remained constant since 1930, and if it is affected by selection, the effect is systematic, and does not depend on completeness of study. The shortest period known for an eclipsing star is that of UX Ursae Majoris ($0^d.1967$), determined by Beljawsky in 1933. There are three or four intrinsic variables known with even shorter periods. Although the period of UX Ursae Majoris is less than five hours, the components have no conspicuous ellipticity and it is therefore an Algol star. All other known eclipsing stars with periods less than three-tenths of a day are of the W Ursae Majoris type, with components of high ellipticity. The longest period known for an eclipsing star is that of ϵ Aurigae ($27^y.08$).

For periods less than half a day the W Ursae Majoris stars predominate; probably all the typical W Ursae Majoris stars are within this interval. The β Lyrae stars appear at periods rather greater than half a day, the Algol stars with periods a little smaller. The former increase slowly in frequency, reaching maximum for a period of about two days; the latter increase rapidly, to a maximum at about the same period.

There are fifty-five eclipsing stars with periods equal to or greater than fourteen days. Most of them are supergiants or giants, with perhaps a few intermediate stars. Detailed investigation of all fifty-five stars has not been made; more than half of them have been inadequately studied, and these would form an interesting and important observational program.

As a rule the period of an eclipsing star remains constant, though not many stars have been long enough observed for finding a change of period. This problem is closely related, though not necessarily always, with the problem of the apsidal motion in an eclipsing system. It can be studied both spectroscopically and photometrically. The most recent investigations of this subject have been made by Luyten[1] and by Dugan and Miss Wright.[2]

Their results with some additional details are given in Table II, I. We denote by 0 the change of period, by + the apsidal motion, by (1) the work by Luyten, and by (2) the work by

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[1] Publ. Astr. Obs., Univ. of Minnesota, 2, No. 2, 1935.

[2] A. J., 46, 148, 1937.

TABLE II, I

CHANGE OF PERIOD AND APSIDAL MOTION FOR ECLIPSING SYSTEMS

Star	Period	Ref.	Star	Period	Ref.	Star	Period	Ref.	Star	Period	Ref.
WZ And	0	2	GL Car[2]	+	..	SZ Her	[0]	2	b Per	+?	1
XZ And	0	2	SV Cen	0	2	u Her[4]	0,+	1	β Per	0,+	1
WW Aur	0?	1	WY Cep	[0]	2	SS Lac	[0]	1, 2	V Pup	+?	1
ζ Aur	[0]	1	AH Cep	0?,+?	1	SW Lac	0	2	μ^1 Sco	+?	1
SV Cam	0	2	U CrB	0	2	AR Lac	[0]	2	U Sge	+?	1
RS CVn	0?	1	Y Cyg	0,+	1	CM Lac	[0]	2	RS Sgr	0	2
R CMa	0	2	SW Cyg	0	2	CO Lac	0,+	2	V523 Sgr[6]	+	..
UW CMa	[+]	1	WW Cyg	0	2	RV Lyr	0	2	V526 Sgr	0,+	2
RZ Cas[1]	0?,+?	1	Z Dra	[0]	1	RU Mon	0,+?	1	RW Tau	0	2
TW Cas	0	2	RR Dra	0	2	RV Oph	[0]	1	α Vir	+?	1
ZZ Cas	0	2	TW Dra[3]	0,+?	..	TY Peg	0	2	Z Vul	[0]	2
AO Cas	0?,+?	1	UZ Dra	[0]	2	RT Per[5]	0,+?	..	RS Vul	0?	1

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[1] Result presented by Pearce, meeting of the American Astronomical Society, 1937, September 10. See, however, Luyten, P.A.S.P., 49, 329, 1937.

[2] The period of apsidal motion is 25 years—the shortest ever found for a star (Swope and Shapley, H.B. 909, 1938).

[3] Result presented by Pearce, December meeting of the American Astronomical Society, 1937.

[4] A recent discussion by Shapley, on the basis of Calder's photoelectric measures, confirms the result (H.C. 425, 1938).

[5] Presented by Dugan, December meeting of the American Astronomical Society, 1937.

[6] Miss Edith Jones, December meeting of the American Astronomical Society, 1937.

Dugan and Miss Wright. The sign ? means questionable, the sign [] means no evidence for it. From this table, containing 48 systems, we can see that only 6 systems have definitely observed apsidal motion, 11 are uncertain, and the rest have given negative results. The change of period has been established for more systems, as is seen from Table II, I. We may finish this section by repeating the words of Dugan and Miss Wright in reference to the mathematical expression of these changes in period:— "but the published sine terms and parabolic terms are found to be of only temporary applicability."

The average period for eclipsing stars of period less than ten day is $2^d.8$, with maxima of frequency at $0^d.6$ and $7^d.0$. There are fourteen known stars with periods less than $0^d.3$, two with periods less than $0^d.25$, and only one with period less than $0^d.2$.

12. **Magnitudes.**—There are only fifteen eclipsing stars suitable for naked-eye observation, and even of these not all were discovered visually. Table II, II illustrates the development of the study of eclipsing stars from the early years, when all discoveries were made, or at least confirmed, visually, to the present day when almost all discoveries are made photographically. Sixteen years ago only ten per cent of known eclipsing stars had been investigated photographically; today the figure is seventy per cent. Furthermore, as time progresses the maximum frequency of apparent magnitude shifts more and more towards fainter stars. Consequently there is an increasingly serious lack of spectroscopic information about newly discovered eclipsing stars, so that our knowledge of their absolute dimensions cannot be expected to grow as fast as the discoveries. Investigations of the colors of eclipsing stars can in some ways replace direct knowledge of spectral classes, and will be of increasing importance in the future.

Table II, III shows the known eclipsing stars that are fainter than the fifteenth magnitude at maximum. Almost all are of short period, and probably belong to the main sequence, a suggestion that is confirmed by the two observed spectra.

TABLE II, II

VISUAL AND PHOTOGRAPHIC INVESTIGATIONS OF ECLIPSING STARS

Apparent Magnitude	Data of 1921			Data of 1937		
	Visual	Photographic	All	Visual	Photographic	All
5.0	7	0	7	9	6	15
6.0	3	0	3	5	6	11
7.0	8	0	8	12	7	19
8.0	15	0	15	13	8	21
9.0	30	7	37	30	44	74
10.0	50	6	56	78	80	158
11.0	34	2	36	75	95	170
12.0	10	0	10	27	85	112
13.0	3	2	5	15	100	115
14.0	0	0	0	1	157	158
15.0	0	0	0	8	71	79
16.0	0	0	0	0	11	11

TABLE II, III

THE FAINTEST ECLIPSING STARS

Star	Period	Maximum	Amplitude$_1$	Amplitude$_2$	D	Class	Spect.
	d	m*	m	m	h		
MR Aql	1.3893	*15.0*	]*1.0*	. . .	. . .	?	. . .
MX Aql	5.849	*15.0*	*1.0*	. . .	. .	?	. . .
GR Car	5.701	*15.3*	*0.5*	. . .	. . .	A	. . .
V363 Cen	2.862479	*15.1*	*0.6*	. .	9	A	. . .
OT Cyg	1.021447	*15.6*	*1.1*	. . .	. . .	?	A1
OU Cyg	0.560327	*15.5*	*0.4*	*0.1*	. . .	?	F3
BG Nor	0.49369	*15.5*	*0.8*	. . .	. . .	?	. . .
RZ TrA	1.5507	*15.3*	*0.8*	. . .	. . .	?	. . .
AS TrA	0.334108	*15.1*	*0.8*	*0.6*	. . .	?	. . .
CY TrA	2.1058	*15.3*	*1.0*	. . .	. . .	?	. . .
DZ TrA	4.943	*15.2*	*1.1*	. . .	. . .	?	. . .

* In this table, and throughout the book, we adopt the convention of printing photographically determined (photographic) magnitudes in italics, and visual (or photovisual) magnitudes in Roman type.

13. Amplitudes.—The change of brightness of an eclipsing star depends on the following elements: ratio of radii (k); ratio of surface brightness (γ); size of eclipsed area (α); ellipticity of components (z); inclination of orbit (i); tidal effect (t); darkening at the limb (d); eccentricity of the orbit (e); reflecting power of components (r); librations of components (l); possible presence of a third body (b); possibility that one or both components have some intrinsic variability (v).

Thus the observed amplitude is a function of at least eleven quantities. Fortunately the contributions of e, l, t, and i are usually very small, amounting in combined effect to no more than $0^m.05$; r, d, and z, though not so small, produce together a change of not more than $0^m.25$, and their effect, except that of d, can easily be removed from the light curve. The fundamental factors, γ, k, and α, make the largest contributions to the amplitude of the light curve. We have, for the amplitude at primary and secondary minimum:

$$\left.\begin{aligned} A_1 &= 2.5 \log\,(1+k^2\gamma)/(1+k^2\gamma - k^2\gamma\alpha) \\ A_2 &= 2.5 \log\,(1+k^2\gamma)/(1+k^2\gamma - k^2\alpha\;) \end{aligned}\right\} \qquad (1)$$

This simple relation enables us to realize, first, the extent of the variation that can be expected, and secondly, how the variations that are observed in practice are limited. The largest observed amplitude is that of RV Apodis (over four magnitudes). Twenty-nine per cent of all observed amplitudes are greater than or equal to three magnitudes, and about six per cent are less than $0^m.4$. The average value of the amplitude at primary minimum is $1^m.4$ for non-elliptical variables, and $0^m.9$ (unrectified) for elliptical variables; in other words, we may conclude that the most frequent amplitude at primary minimum for eclipsing stars in our present list is about $1^m.2$. Regarding the amplitude at secondary minimum we find, with greater uncertainty because of lack of material, an average of $0^m.13$.* It should be mentioned that the amplitude at secondary minimum is, on the average, four or five times greater for elliptical than for non-elliptical variables.

The amplitude furnishes some points of interest. From the formulae given above we may expect minima of any depth, especially when we consider that more than 30 per cent of the observed eclipses are total. Why then are there no eclipses with amplitudes of ten magnitudes, or even cases in which the star disappears completely? The answer must be that there is no eclipsing system in which both components are not self-luminous; but here again we are confronted by a problem, for there are some systems in which γ (the computed ratio of surface brightness) approaches infinity—however, for these systems, the eclipses are not total, but partial. Despite such high values of computed γ, we consider that there is probably no real case in which both components are not self-luminous.

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* But this evidently represents a selection favoring cases where the secondary minimum is deep enough to be easily observable.

Considering the small average amplitudes, we may assume partial eclipses as a first approximation. There are, nevertheless, a number of systems that show annular or total eclipses. A limiting case would be that of a large bright star with a companion of much smaller radius and lower surface brightness. If we could observe an eclipse of the sun by Jupiter, the amplitude would be about $0^m.02$. An interesting system in this respect is SX Normae, with a primary amplitude $0^m.10$, and the ratio d/D of totality to duration of eclipse equal to 0.75; these ratios suggest a ratio of radii less than 0.16. However, the common case in which the larger component eclipses the small one may be occurring here, too, so that we have not yet a sure example of a planetary system.

The simplified relation (1) may be written as follows for the primary minimum in a totally eclipsing system:

$$A_1 = 2.5 \log (1 + k^2\gamma) \tag{2}$$

We recall the expression for γ, derived from the Planck black-body radiation formula:

$$\gamma = \frac{e^{1432/\lambda T_2{}^4} - 1}{e^{1432/\lambda T_1{}^4} - 1} \tag{3}$$

The value of k can usually be derived from the light curve; but when a very small body is eclipsed by a very large one, this determination becomes impracticable. We may then have recourse to Planck's formula.

From (3) it is evident that the amplitude must depend on the effective wave-length of the photometric system in which the observations have been made. The best known example of variation of amplitude with effective wave-length is furnished by ζ Aurigae[3]; the data are shown in Table II, IV. A similar relationship is shown by VV Cephei.[4]

TABLE II, IV

EFFECTIVE WAVE-LENGTH AND AMPLITUDE FOR ζ AURIGAE (GUTHNICK AND OTHERS)

$\lambda_{eff.}$	Max.	Min.	Amp.	$\lambda_{eff.}$	Max.	Min.	Amp.
	m	m	m		m	m	m
3800	5.75	7.89	2.14	5000	4.43	4.70	0.27
4200	5.30	6.22	0.92	5600	3.85	3.98	0.13
4500	4.96	5.45	0.50	5900	3.61	3.72	0.11

14. **Eclipses.**—The possibility of an eclipse depends on the ratio $(r_1 + r_2)/A$, where r_1, r_2, and A are the radii of the components and the distance between the centers. The occurrence of a total eclipse depends, on the other hand, on the ratio $(r_1 - r_2)/A$. Thus, the ratio of possible eclipses to the number of total eclipses is $(r_1 + r_2)/(r_1 - r_2)$, or $(1 + k)/(1 - k)$, where k is r_2/r_1, in accordance with the usual convention. From the observed material we find that out of about nine hundred and fifty systems, three hundred and sixty-three show total or annular eclipses, three hundred and fifty, partial eclipses, and about two hundred and fifty give uncertain results. Thus, the observed ratio of all well-observed eclipses to total or annular eclipses is about 2 — much smaller than would be expected theoretically from the statistically observed mean value, 0.65, for k. The reason for the discrepancy is primarily selection: total eclipses are more likely to be observed than partial ones.[*]

The percentage of total eclipses is more or less constant for all periods up to ten days; and for periods greater than ten days the observed eclipses are total with very few exceptions. Partial eclipses predominate for very short periods. One may see, however, that the actual number of partial eclipses must be much larger than the observed one.

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[3] Guthnick, Schneller, and Hachenberg, Abh.d.Preuss.Akad.d.Wiss., Phys.-Math. Kl., 1935, No. 1.

[4] S. Gaposchkin, H.C. 421, 1937.

[*] From the mathematical point of view it would be better to use not the ratio that we used but the reciprocal of it. For this suggestion we are indebted to Professor Russell.

The duration of the eclipse (D) depends on the ratio of the sum of the radii of the components to the distance between their centers. Where there are two eclipses, we should in the general case have two durations, D_1 and D_2. Although the secondary minimum is difficult to determine and often not well-observed, we have rather complete information about D_2 for many stars. In the section devoted to eccentricity we shall pay particular attention to D_2; here we shall mention only that in 80 per cent of the well-observed systems the ratio D_1/D_2 is near unity, practically consistent with a circular orbit. On the other hand, in some visual observations (probably as a result of psychological factors) the duration D_2 is given as much shorter than D_1—probably shorter than it should be in reality. There are stars for which A_2 is less than $0^m.1$; and it is hard to believe that D_2 could be accurately determinate visually for such stars. The accurate determination of the durations D_1 and D_2 is an urgent future problem which will help us to estimate not only the eccentricity of orbits, but also the direction of motion of the line of apsides.

From the observational material it can be deduced statistically that the duration of eclipse, expressed as a fraction of the period, is on the average 1.5 times smaller for non-elliptical than for elliptical stars. The mean value for all eclipsing systems for which elements have been derived is about 0.15 P, where P is the period. There is a definite relation between the period and the duration of eclipse: the shorter the period, the greater is the duration; it reaches values as great as 0.4 P (AO Cassiopeiae) and as small as 0.04 P (ζ Aurigae), 0.03 (FP Carinae) and 0.025 (TV Normae).

The frequency of inclination of orbit can be discussed both from the theoretical and from the observational standpoint. From statistical considerations it appears that the average value of $(r_1 + r_2)$ should be about 0.5 A; the non-elliptical stars should give a value of about 0.4, the elliptical stars, one of about 0.7. These values lead to approximate limits for the inclination of the orbit, for stars with observable eclipses: 45° for elliptical stars, 66° for non-elliptical stars, or an average of about 60°. If we make allowance for the ellipticity (ratio of c to a), we obtain for elliptical stars a value of 51° for the minimum inclination. When this value is compared with actual observations we find such a low inclination only for the star AO Cassiopeiae (inclination between 51° and 56°). Most of the observed inclinations fall between 80° and 90°, regardless of the type of solution (uniform or darkened) used in the calculation; for all observed eclipsing stars the average inclination is 83°.

15. Spectra.—The spectral classification of eclipsing binaries is in some ways of much more importance than it is for other variables because hitherto the physical characteristics of eclipsing systems have been more accurately determinate than those of other variable stars. Among the 352 eclipsing variables (down to February 1, 1938) there is a large group (271) for almost all of which there exists only the spectral classification made at Harvard. It is known that the system of Harvard has a uniform scale and therefore any discussion of the determinations for this majority will not suffer much from accidental error. In addition, it has been recently found that, in respect to the effective temperatures of stars along the Main Sequence, Miss Cannon's classification is more uniformly built up and has more direct physical significance than other systems. The remaining 62 eclipsing stars have been variously classified and reclassified. Especially is this true of the eclipsing systems for which orbital radial velocities have been obtained. This is not the place for a discussion of the bases of the different classification systems of Mount Wilson, Victoria, Lick, Yerkes, and elsewhere, and their relation to the Harvard system. Indeed, in some of these systems there is still considerable flexibility. In the fifth volume (1935) of the Transactions of the International Astronomical Union the reader may find some indication of the various bases used for spectral classification at the different observatories, from which an idea of the lack of unification may readily be obtained. The discussion by Russell, Payne-Gaposchkin, and Menzel[5] is also of interest in this connection.

Among the observed spectra over 50 per cent are of Class A, about 20 per cent of Class B, about 15 per cent of Class F, and the remainder are distributed among Classes G, O, K, and M.

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[5] Ap.J., 81, 107, 1935.

Finally, the two stars GG Carinae and RY Scuti have spectra of peculiar type, in which bright lines predominate.

The six eclipsing stars with spectra of Class O are shown in Table II, V. They are the most massive eclipsing stars known, and indeed the most massive stars whose masses can be determined individually by dynamical methods. Attention should be called to the large difference in mass between AO Cassiopeiae and 29 (UW) Canis Majoris on one side, and Y Cygni on the other. Even more striking than the mass is the density: AO Cassiopeiae and 29 Canis Majoris have densities of the order of 10^{-3}, and Y Cygni has a density of the order of 0.16. Another point of interest is the smallness of the ellipticity for the stars in Table II, V, although even for AO Cassiopeiae and 29 Canis Majoris the components are very near to one another. One should, however, point out that the two O stars, AO Cassiopeiae and 29 Canis Majoris, are photometrically much more uncertain than Y Cygni.

TABLE II, V

ECLIPSING STARS WITH SPECTRA OF CLASS O

Star	Per.	Type	Max. Mag.	A1	A2	Spectrum
	d			m	m	
SZ Cam[1]	2.70	Ellip.	7.3	0.2	0.2	O9.5
AO Cas[2]	3.52	Ellip.	6.1	0.2	0.2	O8.5 + O8.5
CC Cas[2]	3.37	Non-ell.	7.3	0.1	0.1	O8 + O8
29 CMa[2]	4.50	Ellip.	*4.9*	*0.3*	*0.3*	O7.5[3] + O7.5
Y Cyg	3.00	Non-ell.	6.9	0.6	0.4	O9.5 + O9.5
H.D. 163181[4]	12.00	Ellip.	*6.6*	*0.5*	*0.5*	Oe5

[1] Incompletely investigated as regards light curve.

[2] Incompletely investigated as regards absolute dimensions.

[3] The classification at Yerkes has been given as O9.

[4] Recently discovered eclipsing star (March 1938). Mount Wilson spectrum B1e.

In addition to the incompletely investigated O stars, it should be noted that BM Orionis is here excluded from the list of eclipsing stars. In amplitude and period it is a star of the greatest interest; it is, besides, the faintest star in the Trapezium of Orion, and is therefore involved in nebulosity. Many visual observations of BM Orionis have been made, but no light curve has ever been published; Parkhurst concluded photographically that it does not vary with the previously published period (6.47 days). BM Orionis probably forms a parallel to the very similarly situated star TY Coronae Austrinae, also once considered an eclipsing star, but now known to be an irregular variable situated in nebulosity.[6]

There are several eclipsing stars with spectra of late type, as enumerated in Table II, VI. The list is fairly long, and rich in information. It provides data not only for dwarfs, but also for giants and supergiants.

The predominance of A and B stars among eclipsing systems is a result of their absolute brightness. The A stars are about 100 times brighter absolutely than dwarf G and K stars. Thus, down to the magnitude to which we may regard our knowledge of eclipsing stars as complete, the distance to which we see the A stars, and the volume of space throughout which they are known, will be a thousand times as large; consequently, if they were really equally common, the A stars should appear to be a thousand times as common as the G and K stars. If the correction is applied, it appears that the latter are actually about three hundred times commoner in space.

The spectrum of the first component can be directly observed for the brighter eclipsing stars (down to the eleventh magnitude). For fainter stars it can be immediately deduced from the color index, which is often competent to give not only the combined spectrum, but also the spectrum of the fainter component. Not much of this type of work has been done systematically. Yet it may bring very important information, especially if the color index is accurately measured.

The radii and periods may sometimes be of use in surmising the spectrum, by analogy with other similar systems, although this method can probably not be expected to give results that are correct in detail.

The spectrum of the second component is known for 62 eclipsing variables—about 8 per cent of the whole number of known eclipsing stars.

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[6] S. Gaposchkin, H.A., 105, No. 27, 1936; see Section 50.

Table II, VI

Eclipsing Stars with Spectra of Late Type

Star	First Component		Second Component		Period
	Type	Sp.	Type	Sp.	*d*
RT And	Dwarf	K2	Dwarf	[K8]*	0.63
SY And	Main Seq.	A0	Giant	K1	34.91
RS Ari	Dwarf?	F9	Giant	G5	9.79
ζ Aur	Supergiant	K5	Main Seq.	B9	972.15
ε Aur	Supergiant	F5	Supergiant	?	9890.
i Boo	Dwarf	G2	Dwarf	G2	0.27
SS Cam	Giant	G1	Dwarf	F5	4.82
SV Cam	Dwarf	G3	Dwarf	G5	0.59
RU Cnc	?	F9	Giant	G9	10.17
RZ Cnc	Giant	K0	Giant	K4	21.64
RS CVn	Dwarf	F4	Giant	G8	4.79
U Cep	Main Seq.	A0	Giant	G8	2.49
VV Cep	Supergiant	M2	Main Seq.	B9	7430.
UZ Cyg	Main Seq.	A1	Giant	K1	31.31
RW Dor	Dwarf	M0	Dwarf	[M2]*	0.28
YY Gem	Dwarf	M1	Dwarf	M1	0.81
AW Her	Giant	K2	Giant	G4	8.80
TT Hya	Main Seq.	A3	Dwarf	G6§	6.95
AR Lac	Dwarf	K0	Dwarf	G5	1.98
RZ Oph	Giant	G0	Supergiant	K5	261.94
WZ Oph	Dwarf	G0	Dwarf	G0	4.18
W UMa	Dwarf	F8	Dwarf	F8	0.33
RW UMa	Dwarf	F9	Giant?	G9	7.33
AH Vir	Dwarf	K0	Dwarf	[K5]*	0.41

* Computed from the surface brightness.
§ See the table of elements.

Table II, VII contains a list of all eclipsing stars for which both spectra have been observed. Successive columns contain the name of the star, the maximum brightness, the amplitudes, the period, and the two spectra. The symbols t, a, tp, ap, and p in the last column denote that the principal minimum is "total," "annular," "total partial" (the layer component eclipses the smaller), "annular partial" (the smaller component eclipses the larger), and "partial" (the components are equal). The last column shows the difference in spectra, in units of the spectral class.

TABLE II, VII

ECLIPSING STARS FOR WHICH BOTH SPECTRA HAVE BEEN OBSERVED

Star	Max.	A_1	A_2	Period	Spectra	Ecl.	ΔS
	m	*m*	*m*	*d*			
SY And	10.68	1.50	0.04	34.91	A0 + K1	t	3.1
TW And	8.85	2.0	0.21	4.12	dF0 + G6	t	1.6
WW And	10.3	1.1	?	23.28	A5 + F3	t	0.8
S Ant	6.39	0.44	0.40	0.65	A8 + A8	a	0
σ Aql	4.99	0.18	0.14*	1.95	B8 + B8	p	0
RS Ari	9.79	1.1	0.4	8.80	F9 + G5	t	0.6
β Aur	2.07	0.09	0.09*	3.96	A0p + A0p	p	0
ζ Aur	*4.9*	*0.7*	0.0	972.15	sgK5 + B9	t	–3.6
TT Aur	*8.06*	*0.96*	*0.37*	1.33	B3 + B3	tp	0
WW Aur	5.61	0.64	0.52	2.53	A7 + A7	ap	0
AR Aur	*5.81*	*0.71*	*0.54*	4.13	A0 + A0	ap	0
i Boo	*6.60*	*0.42*	*0.42*	0.27	G2 + G2	p	0
SS Cam	10.1	0.57	0.15	4.82	gG1 + dF5	a	–0.6
SV Cam	8.96	0.64	0.05	0.59	dG3 + dG5†	p	–0.2
UW CMa	4.47	0.34	0.33	4.39	O7 + O7	ap	0
S Cnc	7.97	2.32	0.05	9.48	A0 + G5	t	2.5
RU Cnc	9.94	1.53	0.00	10.17	F9 + G9	t	1.0
RZ Cnc	7.9	1.64	0.26	21.64	K0 + K4†	t	–0.4
RS CVn	*8.12*	*1.91*	*0.08*	4.79	F4 + G8	t	1.4
RW Cap	9.2	1.45	0.24	3.39	A3 + A4†	tp	–0.1
SX Cas	*9.84*	*1.11*	*0.08*	36.57	A6 + G6	t	2.0
TV Cas	7.30	1.05	0.09	1.81	B9 + A0†	tp	–0.1
XX Cas	9.72	0.63	0.31	3.07	B4: + B6:	ap	–0.2
AO Cas	*6.1*	*0.2*	*0.2*	3.52	O8.5 + O8.5	ap	0
CC Cas	*7.3*	*0.11*	*0.11*	3.37	O8 + O8		0
U Cep	6.85	2.34	0.10	2.49	A0 + G8	t	2.8
VV Cep	*6.62*	*0.80*	*0.00*	7430	sgM2 + B9	t	–4.3
AH Cep	6.63	0.22	0.16	1.77	B0 + B0	tp	0
U CrB	7.65	1.02	0.00	3.45	B5 + B9†	t	–0.4
Y Cyg	6.95	0.60	0.40	2.99	O9 + O9†	p	0
UZ Cyg	10.39	1.76	0.06	31.31	A3 + K1	t	2.8
GO Cyg	8.23	0.54	0.23	0.72	B9 + A0†	pa	–0.1
MR Cyg	*8.50*	*0.80*	*0.27*	1.68	A0 + A0:	a	0
TW Dra	7.70	2.34	0.00	2.81	A6 + K2	t	2.6
RX Gem	8.6	2.1	0.0	12.21	A2 + A3†	t	–0.1

* Photoelectric.

† Computed spectrum (from surface brightness) differs considerably from observed spectrum.

TABLE II, VII—*Concluded*

Star	Max.	A_1	A_2	Period	Spectra	Ecl.	ΔS
	m	*m*	*m*	*d*			
RY Gem	8.45	2.05	0.0	9.30	A2 + K2	t	3.0
YY Gem	9.0	0.6	0.6§	0.81	dM1e + dM1e	p	0
Z Her	7.10	0.80	0.12	3.99	F2 + F2	pa	0
RX Her	7.20	0.68	0.60	1.78	A0 + A0	pt	0
TX Her	*8.33*	*0.74*	*0.34*	2.06	A2 + A2	pt	0
AD Her	9.3	2.2	0.0	9.77	A4 + K2	t	2.8
AW Her	9.50	1.44	...	8.80	K2 + G4	t:	−0.8
u Her	*4.60*	*0.68*	*0.28*	2.05	B3 + B3†	pt	0
TT Hya	*7.6*	*2.5*	...	6.95	A3 + dG6p	t	2.3
RT Lac	9.06	1.06	0.61	5.07	G9 + K1	t	−0.2
SW Lac	9.98	0.82	0.69	0.32	G3p + G3p	pt	0
AR Lac	*6.96*	*0.82*	*0.20*	1.98	K0 + G5	pt	−0.5
CM Lac	*8.25*	*1.03*	*0.29*	1.60	A2 + A8	t	0
UX Mon	8.42	1.74	0.14	5.90	A5 + dG1p	t	1.6
U Oph	5.67	0.69	0.59	1.68	B5 + B5	pt	0:
RZ Oph	9.75	0.83	...	261.94	G0 + K5	t	1.5
WZ Oph	9.32	0.74	0.72	4.16	G0 + G0	pa	0
RY Per	8.45	2.03	0.07	6.86	B6 + F8	t	1.8
V Pup	4.14	0.64	0.53	1.45	B1 + B3	pa	−0.2
U Sge	6.52	2.88	0.07	3.38	B9 + G2	t	2.3
V356 Sgr	*6.85*	*1.05*	*0.38*	*8.89*	B9 + A1†	t	−0.2
W UMa	*8.3*	*0.76*	*0.68*	0.33	F8p + F8p	pa	0
RW UMa	9.94	1.00	0.13	7.33	F9 + G9	t	1.0
TX UMa	6.83	2.49	—	3.06	B9 + A3†	t	0.4
Z Vul	6.97	1.63	0.14	2.45	B3 + B3†	t	0
RS Vul	6.90	0.73	0.08	4.48	B8 + B9†	tp	−0.1

REMARKS TO TABLE II, VII

S Ant	Lines are wide and hazy. Much uncertainty in classifying the fainter spectrum.
σ Aql	The secondary is a duplicate of the primary except in intensity.
β Aur	The lines numerous, absorptions are narrow and sharply defined. The spectra are identical and nearly of the same intensity.
TT Aur	Both stars show the helium lines, but with unequal intensity.
WW Aur	Spectra well separated. The lines of the secondary are about 0.8 as strong as those of the primary. The lines are of good quality.

† Computed spectrum (from surface brightness) differs considerably from observed spectrum.

§ The original paper contains indications that the second range is of the same depth as the first range, though current catalogues give only A_1.

AR Aur	Faint indication of $\lambda\lambda$ 4026 and 4471 is discernible.
i Boo	The separation has been made only on one plate; spectroscopically this system has been poorly investigated.
SS Cam	The uncertainty of the second spectrum is due to the presence of the primary spectrum on the same plate.
UW CMa	All lines are dark except the two bands 4633 (NIII) and 4688 (HeII). The emission lines partake of periodic displacement due to the star's orbital motion, just as do the absorption lines. The chief features of the spectrum, 4686, 4640 and 4634, are fairly narrow emission lines, characteristic of a small group of absorption O type stars. The second spectrum is very faint, appearing to be of the same type as that of the primary star.
RS CVn	None of the three plates at primary minimum is entirely satisfactory, as they were taken under poor conditions, but they show that the fainter star is of type K0 and probably belongs to the dwarf branch.
SX Cas	Enhanced line spectrum similar to that of α Cygni. $H\beta$ and $H\gamma$ have bright edges.
TV Cas	The faint lines of the secondary spectrum, approximately of the same type as the primary, have been seen and measured on several plates.
AO Cas	Both appear to be of the same spectrum. The ratio for 4471/4541 is 2.3; for 4541/$H\gamma$, 0.28; and for 4088/4097, 1.35.
CC Cas	The spectrum resembles closely that of AO Cas, but is of slightly earlier type. The strongest lines are the Balmer series. Neutral helium (4471, 4026) is stronger than ionized helium (4686, 4542). Doubly ionized carbon (4651), trebly ionized silicon (4089), and singly ionized nitrogen (4097) are the next strongest lines, followed by the weaker lines of neutral helium. The second spectrum, which appears to be of the same spectral type, is exceedingly faint.
U CrB	The spectrum of the fainter is plainly visible.
Y Cyg	The spectra of both components are visible. The lines are double, of approximately equal strength, and very diffuse and shallow.
GO Cyg	One observation has been secured during the secondary minimum and the spectrum is typical B9n.
RY Gem	$H\beta$ is a weak emission line, and the spectrum is continuous at $H\gamma$.
YY Gem	The spectra of components are unusual. The absorption spectrum pertaining to the more massive component is somewhat stronger than that of the less massive component, approximately in the ratio of 5:4. The stars belong to the small group of M type dwarfs which show H and K and the Balmer series as emission lines. All the bright lines give the same velocities as the absorption lines of the corresponding spectrum. When the velocities are such as to separate the lines, the red member of the pair (emission lines) is, with one or two exceptions, the stronger.
Z Her	The lines of the second spectrum are only about one-half as strong as those of primary, and many are poorly defined or not seen at all on some plates.
RX Her	The spectrum of the star eclipsed at primary minimum is stronger.

TX Her	Both spectra are alike. One plate taken at the primary minimum.
u Her	The spectra resemble closely those of α Virginis. The spectrum of the secondary component is exactly similar to that of the primary, but the lines are of the vanishing order of intensity, and exceedingly difficult to measure.
TT Hya	The spectrum of the secondary (at the primary minimum) contains bright hydrogen lines.
RT Lac	The lines of the brighter component are about three times as strong as those of the primary, which, though the more massive, is in this system the fainter component.
SW Lac	The lines of both components are very diffuse.
AR Lac	The Class K spectrum has sharp emission lines, H and K of CaII, superposed on broad absorption lines.
CM Lac	On some spectra the lines appear to be double, as though two stars of about the same spectral class were present.
U Oph	Second spectrum is extremely difficult to measure.
RZ Oph	In the secondary spectrum (at primary minimum) Hβ is bright and fairly strong. The spectrum is continuous at Hγ.
W UMa	The lines of the primary are slightly stronger than those of the secondary. The spectrum is characterized by extremely wide, shallow lines.
TX UMa	The spectrum at primary minimum is A3.
Z Vul	Second spectrum is practically B3. The spectrum of the fainter component has been measured. There can be no doubt of the reality of its presence.
RS Vul	The second spectrum is extremely difficult to measure.

When the spectrum of the first component is known, and both minima are thoroughly observed, the second spectrum can be deduced from the difference of surface brightness, obtained from a comparison of the minima. The procedure is as follows: we employ a table of relative surface brightnesses, reduced to the sun as zero. Taking from this table the surface brightness of the first component (in magnitudes) corresponding to the observed spectrum of the first component, we add to it the difference (in magnitudes) of surface brightness between the two components, as deduced from the light curve; the result is the surface brightness of the second component, expressed in magnitudes, and the corresponding spectrum may be read off from the table. This method has important results, and enables us to compare the observed spectra with the spectra thus obtained from the light curve. In many cases the agreement is good, but in some cases, such as u Herculis, β Lyrae, Z Vulpeculae, RS Vulpeculae, and the recently discussed TX Ursae Majoris, there is a large discrepancy, amounting to one spectral class.

Table II, VII shows that the largest negative difference in spectra is that of the system VV Cephei, $\Delta S = -4.3$; a negative sign denotes that the spectrum of the heavier component is of the later type, and a positive sign would denote the reverse. The next largest negative difference is that for the system ζ Aurigae, with $\Delta S = -3.6$. The largest positive difference (heavier star of earlier type) is that for SY Andromedae ($\Delta S = +3.1$), and the next is that for RY Geminorum ($\Delta S = +3.0$).

It is of some interest to note that the type of eclipse is related to the difference in spectra. Thus, from 28 systems with $\Delta S = 0.0$, only three—MR Cygni, RX Geminorum, and Z Vulpeculae—have a total eclipse. (RX Geminorum is a strange system with respect to its spectrum; it contradicts all our expectations founded on the period, amplitudes, and the spectrum of the primary.) On the other hand, most systems with very different spectra ($\Delta S >> 0.0$) have eclipses that are total or annular. It is evident that the explanation lies in the relative size of the components; the difference in spectra is closely related to the difference in radii.

In Table II, VII are listed 28 total and 2 annular eclipses. In almost all cases the difference in spectra is considerable and the spectrum at the first minimum should show special features. The remarks to the table contain descriptions of some of the spectra during eclipse. We give here a few additional details. At the Lick Observatory an investigation has been undertaken by Wyse with the special purpose of determining the nature of the spectra during eclipse for 25 systems.[7] Of this number, five secondaries have shown bright hydrogen lines: RY Geminorum, TT Hydrae, RZ Ophiuchi, and probably WW Andromedae and RX Geminorum. The star RW Tauri gave remarkable results. Its spectrum is of Class A0, its amplitude $3^m.4$. At the expected minimum, November 21, 1933, the second spectrum (A0) showed the bright lines of Hβ, Hγ, Hδ, and probably 4481 (MgII); but at the minima of December 16, 1933, and January 10, 1934, there was no trace of the second spectrum or of the bright lines.

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[7] Wyse, L.O.B. 446, 1934.

Several other eclipsing stars have spectral peculiarities at minimum. W Serpentis, which is probably an eclipsing variable,[8] has shown at minimum the bright forbidden lines of ionized iron. During the minimum of the remarkable star VV Cephei the bright hydrogen lines disappear, but the bright forbidden lines of iron do not.[9]

The puzzling system ϵ Aurigae shows no appreciable change of spectrum during the total eclipse (over 300 days). Its lines become somewhat stronger, and some display an asymmetry (for example, 4468), during the ascending branch of the light curve.[10]

The classical system ζ Aurigae shows no peculiarities during the eclipse, but at the beginning and end there is an indication of the existence of an atmosphere around the supergiant K5 star.

The data concerning spectra (observed and inferred) for 220 eclipsing stars are summarized in Table II, VIII. From Tables II, VI; II, VII; and II, VIII one can judge how many of the faint spectra have been observed, and how many computed.

TABLE II, VIII

SPECTRA OF ECLIPSING STARS

Component	O7–O9	B1–B7	B8–B9	A0–A1	A2–A9	F0–F9	G0–G9	K0–K9	M
Bright	3	16	22	51	56	23	30	17	3
Faint	3	10	6	16	23	42	62	50	8

We may mention here that there appears to be no one-parameter relation between spectrum and period. Martinoff recently came to the same conclusion statistically.[10a] We shall show, however, on subsequent pages, that the period, spectrum, and mass can be expressed by a simple analytical formula.

16. Radii.—Computations of the absolute dimensions of the components are chiefly dependent on the spectroscopically determined masses and on the period. They depend also, statistically, though to a less degree, on the duration of eclipse. Masses have been determined spectroscopically, with considerable certainty, for 35 eclipsing systems, but the number of determinations can be increased to over 250, as is explained in the section devoted to masses.

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[8] S. Gaposchkin, H.A., 105, No. 27, 1936; O'Connell, Bosscha Ann., 8, 22, 1937.

[9] S. Gaposchkin, H.C. 421, 1937.

[10] Frost, Struve, and Elvey, Publ. Yerkes Obs., 7, Part 3, 1932.

[10a] Rus. A. J., 14, 306, 1937.

Other methods of determining the radius may be mentioned here. The first, developed by Lundmark,[11] depends on a certain statistical correlation between mass and radius; the correlation coefficient has the large value +0.802±0.096. Similar methods have been used by Holmberg[12] and Pilowski.[13] Another method has been suggested by Kreiken,[14] involving the use of the theoretical mass-luminosity relation.

Considering the absolute dimensions of eclipsing stars, we note that the largest value is that for the red component of VV Cephei (2400 ⊙), and the smallest that for UX Ursae Majoris (0.3 ⊙): a ratio in size of seven thousand. In the former system there is a large secondary variation caused by the fluctuations of the brighter star. Although UX Ursae Majoris has the shortest known period for an eclipsing star, it is nevertheless described as of Algol type, so that the ellipticity of the components, if any, must be very small.

A more detailed study of dimensions leads to the following results: Among the three O stars, AO Cassiopeiae and 29 Canis Majoris have nearly equal radii (23 ⊙), and Y Cygni a much smaller radius (about 5 ⊙). One must, however, remember that for the first two the photometric elements are of much lower accuracy than those for Y Cygni. Among the B stars, too, there is a variety of radii: β Lyrae and RY Scuti* (if indeed the latter is a Be star) have almost equal radii (about 18⊙). For the other 38 eclipsing stars of Class B we find a mean radius of 4 ⊙. The A stars have a range from 0.8 ⊙ (for RW Monocerotis) to 32 ⊙ (for SX Cassiopeiae). Excluding three systems

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[11] Lund Circ. 5, 1932.
[12] Lund Medd., Series 2, No. 71, 1934.
[13] Zs. f. Ap., 11, 265, 1935.
[14] A.N., 259, 349, 1936.
* These stars are very peculiar; indeed, the duplicity of RY Scuti has not yet been confirmed spectroscopically.

(FP Carinae, 14 ⊙; SX Cassiopeiae, 32 ⊙; and AM Aurigae, 14 ⊙) we find, for 104 stars of Class A0-A9, a mean radius of 3 ⊙. Among the F stars ε Aurigae must be excluded in taking the mean; and Class G is naturally divided into two groups, as is Class K. The mean radii are summarized in Table II, IX.

TABLE II, IX

RADII OF ECLIPSING STARS (IN SOLAR RADII)

Class	O	B	A	F	dG	gG	dK	gK	dM
Radius	23; 5	4	3	2	1	24	0.8	100	0.8
Number	2 1	36	104	22	7	6	5	2	1

The range of radius within any one spectral class is considerable, and therefore the values given in this table are not of great significance. They show only the general tendency. There appears, however, to be a sharp increase in size between the B and O stars, and a continuous decrease of radius along the Main Sequence. We give below the radii computed by the formula:

$$R_h = \frac{1}{q} A = \frac{1}{q} \sqrt[3]{(m_1 + m_2)\, P^2\, 74.4}, \text{ and by } R_l = kR_h.$$

The masses, period, *q*, and *k* have been taken from the table in the following section on masses. The subscripts *l* and *h* denote "light" and "heavy," respectively.

17. Masses.—The masses of stars deduced from eclipsing systems can be placed in importance beside the masses deduced from visual binaries. As eclipsing systems cover a much larger range of masses than most visual binaries, they are exceedingly important subjects in a study of masses.

Since 1932 several remarkable eclipsing systems have been either discovered or their properties established: ζ Aurigae (B + K), AH Cephei (B+B), UW Canis Majoris (O + O), and VV Cephei (B + M) extend our knowledge of the upper end of the series of stellar masses; CM Lacertae (A + A), AR Aurigae (A + A), WZ Ophiuchi (G + G), MR Cygni (A + A), TX Ursae Majoris (B9 + A3), and the redetermination of i Bootis (G + G) cover the middle and lower end of the series of masses.

TABLE II, X

MEAN RADII (COMPUTED)

	Radius			Radius	
Star	Heavy	Light	Star	Heavy	Light
S Ant	1.17	0.80	YY Gem	0.98	0.90
σ Aql	3.55	3.55	Z Her	3.02	2.14
TT Aur	2.95	2.53	RX Her	1.82	1.82
WW Aur	2.14	2.06	TX Her	1.74	1.78
AR Aur	1.91	2.07	u Her	4.47	4.96
β Aur	3.31	3.31	RT Lac	6.31	6.31
ζ Aur	245	4.90	CM Lac	1.26	1.01
i Boo	0.61	0.52	AR Lac	1.78	2.96
RS CVn	3.39	5.29			
TV Cas	2.24	2.73	U Oph	2.82	3.13
AO Cas	22.9	13.9	WZ Oph	1.29	1.25
UW CMa	17.0	14.1	AG Per	3.72	2.25
VV Cep	2400	24.0	V Pup	6.92	6.29
AH Cep	5.37	4.03	U Sge	2.00	2.06
U Crb	3.03	6.30	W UMa	0.79	0.63
Y Cyg	4.37	4.37	TX UMa	1.3	1.9
GO Cyg	1.51	1.00	Z Vul	3.31	5.72
MR Cyg	2.45	1.71	RS Vul	4.51	9.02

There were several attempts mentioned above (p. 39), to find a correlation between the masses and other properties of eclipsing binaries. A detailed discussion of this problem will be published elsewhere.[15] We give here only the necessary arguments and results concerning the masses. An eclipsing system without doubt obeys the third law of Kepler, the Stefan-Boltzmann law of radiation, and probably the mass-luminosity law of Eddington. Thus we have three fundamental relations for a double system: $m_1 + m_2 = c_1A^3 P^{-2}$; $L = c_2R^2 T_e^4$; and $L = c_3M^{3+p}$, where the notations are familiar to everyone; p denotes a number unknown, but in general near to zero. According to most statistical discussions on the subject, for rather limited material on masses, p may be placed at either 0.0 or 0.2, the latter value being somewhat more frequently adopted.

The derivation of a formula for the mass of the heavier component has been carried out in the following way. First we expressed the radius of the star in units of A (distance between the centers), then, combining the three formulae given above, we found that the mass for the heavier component can be expressed by the formula:—

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[15] Am. Philos. Soc., *in press*, 1938.

$$\log m = \frac{2}{7+3p} [1.8716 + \log (1+\alpha) + 2 \log P + 6 \log T - 3 \log q] \quad \text{(a)}$$

Here m denotes the mass of the heavier component, expressed in the solar units; α is the ratio of masses, always less than, or equal to, 1.0; P is the period of revolution, expressed in days; T is the effective temperature of the star, expressed in the solar units; q is the reciprocal of the radius in the units of A.*

Our purpose is to show how to obtain the masses in eclipsing systems, knowing only the period, spectrum, and light curve. In the above equation, P and q can be found from the light elements, T can be taken from the temperature scale for a given spectrum, and α can be found from the correlation between the ratio of masses and the ratio of luminosities.

There are 35 eclipsing systems for which the masses are well determined; that is, the orbital radial velocities of both components have been measured. In the next table we give the essential values for these most important eclipsing binaries. The reader may find the additional information on radii and spectra on previous pages.

From the values of $1 + k$, where k is the ratio of the heavier to the lighter, one can see that for 18 systems *the larger star is the more massive one*; one sees too that the largest star in respect to the distances between the centers appears to be in the difficult system AO Cassiopeiae; the radius occupies more than half of the distance ($R = 0.6A$). After this system come GO Cygni, UW Canis Majoris, and S Antliae. In respect to mass, period, and spectrum behavior GO Cygni is the most peculiar eclipsing variable in the list. To these three systems must be added W Ursae Majoris and V Puppis. In all five the radius of the heavier component is somewhat larger than one-third of the distance between the centers. The reliability of the mass determinations is without doubt much better than that of the values for the

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* q, in other words, could be expressed in terms of the r_b or r_f symbols used in practice for the relative radii, so that $-3 \log q = + 3 \log r$.

TABLE II, XI

OBSERVED MASSES OF ECLIPSING STARS

Star	Period	Masses		α	$1+k$	q	Number Lt. C.
		heavy	light				
S Ant	0.65	0.75	0.42	0.56	1.73	2.8	2
σ Aql	1.95	6.19	5.14	0.81	2.00	4.45	1
TT Aur	1.33	6.70	5.3	0.80	1.86	3.88	3
WW Aur	2.53	2.20	1.90	0.86	1.96	5.02	2
AR Aur	4.13	2.68	2.50	0.93	2.09	9.56	1
β Aur	3.91	2.40	2.36	0.99	2.00	6.80	3
ζ Aur	972.15	16.4	9.5	0.59	1.02	5.01	3
i Boo	0.27	0.64	0.64	1.00	1.86	3.20	2
RS CVn	4.80	1.85	1.74	0.94	2.06	5.02	5
TV Cas	1.81	1.83	1.01	0.55	2.22	4.00	8
AO Cas	3.52	36.3	33.8	0.93	1.65	1.09	2
UW CMa	4.39	40.3	30.8	0.75	1.83	2.68	1
VV Cep	7430.	44.5	35.6	0.80	1.01	2.80	1
AH Cep	1.87	14.6	12.6	0.87	1.75	3.37	1
U CrB	3.45	7.0	2.7	0.38	3.08	6.70	6
Y Cyg	3.00	17.6	17.4	1.00	2.00	6.10	2
GO Cyg	0.72	1.04	0.88	0.85	1.66	2.60	2
MR Cyg	1.68	3.04	2.59	0.85	1.70	3.30	1
YY Gem	0.81	0.63	0.57	0.91	1.89	5.00	1
Z Her	3.99	1.6	1.3	0.81	1.70	4.88	4
RX Her	1.78	2.2	1.9	0.86	2.00	5.23	4
TX Her	2.01	2.06	1.77	0.88	2.01	7.18	4
u Her	2.05	7.52	2.87	0.38	2.11	3.20	9
RT Lac	5.07	5.00	1.00	0.20	2.00	3.57	4
AR Lac	1.90	1.42	1.41	1.00	2.61	7.05	2
CM Lac	1.60	2.01	1.51	0.75	1.80	5.30	1
U Oph	1.68	5.36	4.71	0.89	2.11	4.59	2
WZ Oph	4.16	1.41	1.35	0.96	1.98	12.1	1
AG Per	2.03	5.2	4.6	0.90	1.70	3.78	1
V Pup	1.45	21.2	16.3	0.77	1.91	2.55	2
U Sge	3.38	6.70	2.03	0.30	2.33	4.57	4
W UMa	0.33	0.75	0.54	0.72	1.80	2.73	7
TX UMa	3.06	3.03	0.91	0.30	2.43	7.14	1
Z Vul	2.45	5.34	2.36	0.44	2.73	4.54	5
RS Vul	4.48	5.26	1.64	0.31	3.00	5.00	6

radii. The different solutions based on different light curves have very little effect on the masses, but they may affect the radii by as much as 50 per cent. Therefore the last column in the table contains the number of light curves used. In this respect the data for the majority of the systems have considerable

TABLE II, XII

SPECTRA AND AMPLITUDES FOR ECLIPSING STARS

Star	Spectrum	Amplitudes Primary	Amplitudes Secondary	Obs.	$\sqrt[3]{abc}$
		m	m		
S Ant	A8 + A8	0.44	0.40	v	0.78
σ Aql	B8; B8 + B8	0.18	0.14	ph	0.95[1]
TT Aur	B5; B3 + B3	0.96	0.37	p	0.83
WW Aur	A0; A7 + A7; A4sp	0.64	0.52	v	1.00
AR Aur	B9; A0 + A0	0.71	0.54	p	1.00
β Aur	A0p; A0p + A0p; A1np	0.09	0.09	ph	0.98
ζ Aur	K0 + B1; cK4 + B; K5 + B9	0.7	(0.12)	p (v)	1.00
i Boo	G2 + G2	0.42	0.42	p	0.92[2]
RS CVn	F8; F4n + dG8	1.92	0.08	p	(0.93)[3]
TV Cas	B9; A0 + A0; B5 + B9	1.05	0.09	v	0.95
AO Cas	B0; O8. 5nk + O8. 5nk	0.2	0.2	ph	0.93[4]
UW CMa	Oe; O7sfk + O7sfk; O9sfk	0.34	0.33	p	0.88[1]
VV Cep	Map; M2e + B9	0.8	—	p	1.00[5]
AH Cep	B3; B0nk + B0nk	0.22	0.16	v	0.87
U CrB	B8; B5 + B9	1.02	—	v	0.97[6]
Y Cyg	B2; O9nnk + O9nnk	0.60	0.40	v	1.00
GO Cyg	A0; B9n + A0n	0.54	0.23	p	0.90
MR Cyg	A0; A0 + A0	0.71	0.15	v	1.00[7]
YY Gem	M1ep + M1ep	0.60	0.60	p	1.00[1]
Z Her	F5p; F2p + F2p	0.80	0.12	v	1.00
RX Her	A0; A0 + A0	0.68	0.60	v	0.95
TX Her	A5; A2 + A2	0.70	0.34	p	1.00
u Her	B3; B3 + B3	0.68	0.28	ph	0.93[8]
RT Lac	G5 + K1	1.06	0.61	v	0.93
AR Lac	G5; G5 + K0; G3 + G2	1.03	0.29	p	1.00
CM Lac	A2 + A8	0.85	0.20	p	1.00
U Oph	B8; B5nk + B5nk	0.69	0.59	v	0.93
WZ Oph	G0; G0 + G0	0.74	0.72	v	1.00[9]
AG Per	B3; B3k + B3k	0.30	0.23	p	1.00
V Pup	B1; B1 + B3	0.64	0.53	v	0.87
U Sge	B9; B9 + G2	2.88	0.07	v	1.00
W UMa	G0; F8p + F8p	0.76	0.68	p	0.82
TX UMa	B8; B9 + A3	2.49	—	t	1.00[10]
Z Vul	B3; B3 + B3	1.63	0.14	v	0.90[2]
RS Vul	B8; B8 + B9	0.73	0.08	v	0.97

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[1] New light curve needed.

[2] New spectroscopic observations needed.

[3] New light curve and new discussion of this star needed.

[4] A new infrared photoelectric light curve has been obtained by Bennett. We had the privilege of seeing it, and there is no longer any doubt that it is an eclipsing system, with very close components.

Notes to Table II, XII—*Continued*

[5] New eclipsing binary, which deserves more attention.

[6] The absolute dimensions have been derived from Pearce's spectroscopic elements (P.A.A.S., 8, 220, 1935) and mean values: $i = 75°$, $q = 6.7$, $k = 0.50$.

[7] The absolute dimensions have been derived by one of the writers on the basis of material published by Johnson (A.J., 43, 37, 1933) and Pearce (J.R.A.S.C., 29, 412, 1935).

[8] New spectroscopic elements, especially determination of the spectral class, needed.

[9] This eclipsing binary (H.B. 907) may be regarded as one of the best determined systems from the photometric point of view.

[10] The elements of Rügemer were used.

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weight in the determination of radii. The information of Table II, XI is complemented by that in Table II, XII, where we summarize the spectral classification, which, when interpreted physically, becomes one of the most important factors in the analysis of eclipsing binaries. We have already mentioned that there are different systems of classification, and that they do not necessarily coincide with one another, which, of course, makes any precise discussion very difficult. The first letter refers usually to the Harvard classification; the others are chiefly Mount Wilson or Victoria. The spectra of the two components are connected with a plus sign. In the next column we include the amplitudes, which give definite information as to the accuracy of the light elements. Then follows the abbreviation for the kind of light curve: ph, photoelectric; v, visual; p, photographic. In the last column we give the mean radius in the unit of the semimajor axis, from the relation $r = \sqrt[3]{abc}$. The combination of Tables II, X; II, XI; and II, XII gives complete information on the thirty-five eclipsing systems for which the absolute dimensions have been best determined.

After having given this detailed information about the material, we can proceed to compute the masses of eclipsing binaries. First, for 35 heavier components we make two assumptions as to the value of p in the mass-luminosity relation, namely, $p = 0.0$ and $p = 0.2$. The results are represented in Table II, XIII.

For the computation we adopted the latest spectral determinations, and the temperature scale given by Russell, Dugan, and Stewart.

TABLE II, XIII

Star	Adopted Temperature	Computed Mass		Observed Mass
		$p = 0.0$ $\odot$	$p = 0.2$ $\odot$	$\odot$
S Ant	7800°	1.98	1.88	0.75
σ Aql	12400	5.81	5.07	6.19
TT Aur	18000	9.57	8.05	6.70
WW Aur	8500	2.32	2.17	2.20
AR Aur	11000	3.93	3.53	2.68
β Aur	10400	4.01	3.61	2.40
ζ Aur	3300	17.6	14.0	16.4
i Boo	5700	0.54	0.57	0.64
RS CVn	6700	2.88	2.65	1.85
TV Cas	11000	4.38	3.91	1.83
AO Cas	26000	65.1	47.3	36.3
UW CMa	25000	51.4	37.9	40.3
VV Cep	2500	48.8	36.9	44.5
AH Cep	18000	13.0	10.6	14.6
U CrB	15000	9.5	7.6	7.0
Y Cyg	24500	18.8	15.2	17.6
GO Cyg	11700	4.65	4.13	1.04
MR Cyg	11000	1.92	1.82	3.04
YY Gem	3200	0.31	0.37	0.63
Z Her	7100	2.98	2.74	1.6
RX Her	11000	3.90	3.52	2.2
TX Her	9900	2.70	2.50	2.06
u Her	18000	14.3	11.6	7.52
RT Lac	5200	2.70	2.50	5.00
AR Lac	5400	0.89	0.90	1.42
CM Lac	9100	2.95	2.72	2.01
U Oph	15000	7.12	6.37	5.36
WZ Oph	6000	1.14	1.10	1.41
AG Per	18000	12.2	10.0	5.2
V Pup	21400	22.4	17.6	21.2
U Sge	11700	6.63	5.73	6.70
W UMa	6100	0.86	0.95	0.75
TX UMa	11700	4.40	3.9	3.03
Z Vul	18000	11.3	9.38	5.24
RS Vul	12400	5.62	4.90	4.60

Table II, XIII shows that in general the computed mass is in agreement with the observed one, and that the mass-luminosity relation is in many cases better represented with $p = 0.2$ than with $p = 0.0$. We may note that it is rather surprising that relatively ill-determined systems like UW Canis Majoris, VV Cephei, i Bootis, ζ Aurigae, and σ Aquilae show a good agreement, while such systems as TT Aurigae, AR Aurigae, β Aurigae, and many other well-determined systems show a much larger deviation. Especially, the relatively newly established system GO Cygni shows the largest deviation, the computed mass being more than four times larger than that observed.

On the average, the computed mass is 1.3 times larger than the observed one for $p = 0.0$, and only 1.07 times larger for $p = 0.2$. In taking means we have excluded GO Cygni. It may be noted that YY Geminorum (Castor C), which seems to be a well-established system, shows the largest negative difference.

It is evident that the cause of discrepancy may not only lie in the possibility that stars having some essential characteristics alike will be unlike in other characteristics, contrary to our expectation; but it may lie also in the errors of observation or in the adopted values of the temperatures. It is scarcely likely, however, that the latter will have been taken too high, for other systems of effective temperature give even higher values. Another source of uncertainty is the spectral classification itself. The fourth source of uncertainty is the photometric determination of the radius; it is well known that light curves with shallow minima lead to radii that are larger than those obtained from light curves with well-defined, deep minima ($A_1 = 0^m.4$). All these factors together can easily explain our numerical differences in the masses.

The relation on page 42 can be used for two different purposes: (1) the determination of the masses of the components when the period, spectrum, and light curve are known; and (2) the determination of the temperature, given the mass, period, and light curve. The problem cannot be treated here in detail. Before leaving the subject of masses, we may note that eclipsing systems show a rather continuous increase in mass along the spectral series. There are not such large gaps as exist between the Trumpler stars and the heavy eclipsing systems.

18. Densities.—The simplest way to compute the density of a star is from the relation $\varrho = \frac{M}{R^3}$ expressed in solar units. The masses and radii should be found independently. Where no orbital velocities are available, the mass may be derived from the relation on page 42. In accordance with the proposal of Russell the density could be found directly from the period and the relative dimensions obtained from the light curve. If $R = \frac{A}{Q}$, and $A^3 = M(1 + \alpha) \cdot P^2 \cdot 74.4$, then $\varrho = \frac{Q^3}{74.4\, P^2\, (1 + \alpha)}$; Q is the value obtained from the light curve,* and α is the ratio of masses, which is statistically (for example, from Table II, X) very near to 0.75. Thus for 28 eclipsing systems, α varies from 0.55 to 1.00 with the mean value 0.83, and with seven additional systems, for which α lies between 0.20 (RT Lacertae) and 0.44, it becomes 0.74. There is no definite relation between α, the ratio of the masses, and the relative luminosity L. As the first approximation, however, the following form may be used,

$$\alpha = 0.20 + 1.6\,(1 - L_b)$$

The formula proposed by Russell will in any case be of great use.

A statistical investigation of more than two hundred densities leads to some general results, which are embodied in Table II, XIV. The entries of this table, if plotted, follow the well-known features of the Russell diagram, mean density being substituted for luminosity.

In order not to be misunderstood we should mention that in Table II, XIV the 35 systems with fully determined absolute dimensions are included and are treated statistically, that is, some mean values of ϱ have been adopted, not the direct determinations from observation. Further, it is important to realize that many spectra of faint components have been deduced from surface brightnesses, which are taken from the catalogue of elements (Table II, XXII).

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* Q is the same as *q* on page 42.

TABLE II, XIV

DENSITIES AND SPECTRA FOR ECLIPSING STARS

	Main Sequence				Giant Stars			
	Bright Component		Faint Component		Bright Component		Faint Component	
Spectrum	Mean Density	No. of Stars	Mean Density	No. of Stars	Mean Density	No. of Stars	Mean Density	No. of Stars
O7–O9	0.049	3	0.051	3	...	...	...	...
B1–B7	0.08	16	0.06	10	...	...	...	...
B8–B9	0.11	22	0.08	6	...	...	...	...
A0–A1	0.32	51	0.12	13	...	...	...	...
A2–A3	0.36	29	0.37	7	...	...	...	...
A4–A5	0.25	18	0.16	10	...	...	...	...
A6–A9	0.12	9	0.16	6	...	...	...	...
F0–F4	0.36	15	0.16	20	...	...	...	...
F5–F9	0.37	8	0.19	19	3×10^{-6}	1*	3×10^{-9}	1**
G0–G4	1.60	4	0.94	8	0.0014	4	0.045	29?
G5–G9	2.90	3	1.00	1	0.0035	23	0.04	23?
K0–K9	2.80	17	2.70	12	0.001	3	0.02	38?
M	3.2	2	4.9	3	3×10^{-9}	1*	0.004	6?

* Supergiants.

** After an investigation of this star ε Aurigae (see the end of chapter), it appears that it has a much later spectrum, for its computed temperature is about 1100°.

19. Temperature and Absolute Magnitude. *Temperature.*—We have said that the eclipsing variables provide two methods for obtaining effective temperatures for stars of various spectral classes. The first method consists in deriving the temperature when the parallax and absolute dimensions are known. The uncertainty of the parallax makes this method difficult, as is seen from the formula[16]:

$$\log T = 0.10\,(-0.15 - m - 5 \log R - 5 \log \pi + \Delta M) + 3.769,$$

where T is the effective temperature; m, the apparent magnitude; R, the radius (in solar units); π, the parallax; and ΔM, the bolometric correction. The system of μ Scorpii is one of the best for the application of the method, because of its known parallax and its well-determined photoelectric light curve and spectroscopic elements[16a]; it was the first early B star for which data of this kind were obtained. Another method for deriving the temperature results from a discussion of the masses. (See Section 17.)

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[16] S. Gaposchkin, A.N., 248, 213, 1933.

[16a] P. Rudnick and Elvey, Ap.J., 87, 553, 1938.

In the following table we give several temperature scales for purposes of comparison. When two values are given in the last column they represent limits.

TABLE II, XV

THE TEMPERATURE SCALE

Spectral Class	Russell, Dugan Stewart (mean)	Payne (ionization)	Gaposchkin (parallax)	Gaposchkin (masses)
O7	28000:°	28000:°	29000°	28200°
B0	23000	20000	20900	20500
B5	15000	14800	14300	14300
A0	11000	10000	10700	8910
A5	8600	8710	8910	7590
A8	7980	7940	8510	7080 6500
F0	7400	7410	7940	6610 6310
F5	6500	6460	6310	6030 3310
G0	6000 5600	5500	5500	5890 3020
G5	5600 4700	4680	4900	5370 2880
K0	5100 4200	3980	4170	5250 2760
K5	4400 3400	3390	3720	4470 2600
M0	3400 3000	2950	3240	4270 2400

Absolute Magnitude.—There are two methods for determining the absolute magnitude of an eclipsing system. For stars of known parallax we may use the relation

$$M = m + 5 + 5 \log \pi,$$

and where radius and spectrum are known we make use of

$$M_{bol} = M - 5 \log R - 10 \log (T / T_{\odot})^{*}$$

in accordance with the Stefan-Boltzmann law of radiation.

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* Originally derived by Eddington.

Using the Planck law of radiation, Russell, Dugan and Stewart have derived the valuable formulae:

$$M_{vis} = -5 \log R + 29500/T_e - 0.08$$
$$M_{pg} = -5 \log R + 36700/T_e - 0.72$$

The following relation, deduced from Stefan's law, may be used,**

$$M_{vis} = 10 \log (c_2/T) - 5 \log R + 0.93 + \Delta M,$$

where ΔM is the bolometric correction for the temperature concerned; in deducing this formula the following solar values were adopted: $c_2/T = 14320/5784$, $M = +4.85$. The quantity ΔM may be calculated from the following formula:

$$\Delta M = 2.3\ (14300/T_e)^{0.93} + 10 \log T_e - 42.9$$

The absolutely brightest eclipsing system is 29 Canis Majoris ($M_{vis} = -7$), exceeded only by a few stars such as S Doradus, and by certain novae at maximum. One should remember, however, that there is considerable uncertainty in this derived absolute magnitude. The absolutely faintest eclipsing system is YY Geminorum (Castor C) with an absolute magnitude +9; and probably UX Ursae Majoris ($\pi = 0''.02$, $M_{vis} = +8.57$) is almost as faint. In other words, the observed range in absolute magnitude among eclipsing stars is sixteen magnitudes, or a range of intensity of one to two and a half million. The range in radii, it will be remembered, is about one to seven thousand.

TABLE II, XVI

ABSOLUTE MAGNITUDES OF ECLIPSING STARS

Range of Magnitude	Number of Stars	Range of Magnitude	Number of Stars	Range of Magnitude	Number of Stars
M M	Per cent	M M	Per cent	M M	Per cent
]−2.0 to −2.0	2	0.0 to 1.0	23	3.0 to 4.0	15
−2.0 to −1.0	3	1.0 to 2.0	22	4.0 to 5.0	8
−1.0 to 0.0	2	2.0 to 3.0	20	[5.0	5

The distribution of the known eclipsing stars in absolute magnitude is shown in Table II, XVI.

** Derived by one of the authors in 1932.

In Table II, XVII, the distribution of the spectra of eclipsing stars is summarized for various intervals of absolute magnitude.

TABLE II, XVII

SPECTRUM AND ABSOLUTE MAGNITUDE FOR ECLIPSING STARS

Main Sequence Stars									Giant Stars		
Spectrum	Abs. Mag.	No. Stars	Spectrum	Abs. Mag.	No. Stars	Spectrum	Abs. Mag.	No. Stars	Spectrum	Abs. Mag.	No. Stars
O8	−5.6	3	A2.2	1.50	30	dG1.5	4.4	8	gG1	−1.3	6
B3	−1.4	18	A5.4	1.91	30	dG7	5.8	6	gG5	−1.7	3
B8.5	−0.05	21	F0.7	2.09	26	dK0	6.1	17	gK2	−3.1	2
A0	0.68	60	F6.3	2.97	19	dK5	8.2	1	...	...	...
						dM1	8.8	2	gM2	−5.0	1

20. Radial Velocities.—The range in radial velocity depends, according to the third law of motion, on the masses of the components and the period of the system. The behavior of eclipsing stars in this respect is in full accordance with the behavior of spectroscopic binaries, as studied by Beer[17]. The mean values for the range of velocity of the brighter component are summarized in Table II, XVIII.

TABLE II, XVIII

RANGE OF RADIAL VELOCITY FOR ECLIPSING STARS

Spectrum	Amplitude		Period	No. of Stars	Spectrum	Amplitude		Period	No. of Stars
	K_1	$KP^{1/3}$				K_1	$KP^{1/3}$		
	km /sec		*d*			km /sec		*d*	
O8	210	340	4.2	4	F5	90	125	2.7	5
B2	170	257	3.5	15	K0	120	151	2.0	1
B9	90	128	2.9	7	M1	114	106	0.8	1
A2	87	115	2.3	19	M2	20	320	7430	1

21. Galactic Distribution.—The eclipsing stars embrace so large a variety of spectra that the galactic distribution cannot be expected to show any striking features. The relation between period, spectrum, and galactic latitude, if it were well-marked, would provide a means of estimating the colors of faint stars, and therefore the dimensions could be found from an application of the mass-period-spectrum relation. A detailed study of the periods of 638 eclipsing stars, however, reveals no sign of correlation between the elements mentioned. Between spectrum and galactic latitude there is, however, a rather well-marked relation (Table II, XIX). The mean value of the galactic latitude is 19°, indicating that the general galactic concentration of eclipsing stars is not very well marked. The galactic distribution for eclipsing stars of the various spectral classes is not very different from that of all stars of comparable brightness belonging to the same classes.

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[17] Veröff.Ber.-Bab., 5, Figure 1, 1927.

TABLE II, XIX

SPECTRUM AND GALACTIC LATITUDE FOR ECLIPSING STARS

Spectrum	Mean Galactic Latitude	Number Stars	Spectrum	Mean Galactic Latitude	Number Stars
O	6°	6	G	25°	18
B	6	60	K	26	6
A	17	155	dM	22	1
F	24	33	gM	7	1

22. **Eclipsing Systems as Standards for Theoretical Problems.**—It was Eddington[18] who first realized the importance of eclipsing variables in the study of stellar interiors. In both English and German editions of "The Internal Constitution of The Stars" he made a comparison between the luminosities obtained from observation in accordance with the relation:

$$L = C\,R^2\,T^4,$$

and the luminosities obtained from his theory:

$$L \propto M^{7/5}\,(1-\beta)^{3/2}\,\mu^{4/5}\,T^{4/5},$$

where $(1 - \beta)$ is the ratio (radiation pressure/total pressure) and μ is the molecular weight. His comparison material (thirteen stars) confirms the mass-luminosity relation. In 1932 one of the writers[19] made a similar investigation of twenty-five eclipsing stars, with results that were in good agreement with Eddington's, so that the relation

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[18] The Internal Constitution of the Stars (German edition), 180, 1928.

[19] S. Gaposchkin, Veröff. Ber.-Bab., 9, Part 5, 1932.

$$L \propto M^{3.2}$$

may be adopted for practical purposes.

A second application of eclipsing star data was made by Bengt Strömgren[20], which confirmed the growing opinion that the hydrogen content of the stars is an important factor in stellar models. There is no unique relation between mass (M), luminosity (L), radius (R), molecular weight (μ), and hydrogen content (X); Strömgren chooses values of μ and X to fit the observed values of L, M, and R. The Russell diagram (spectrum and absolute magnitude) may be interpreted as a mass-hydrogen content diagram. Two stars of equal mass but different radius have different hydrogen content; the larger star has the smaller percentage of hydrogen.

A third application has been made by Chandrasekhar,[21] who has discussed stellar envelopes and the central condensation of stars, as had previously been done for Capella by Eddington. In regard to eclipsing stars he confined himself to the central portion of the series. It is of some interest to inquire whether the smallest eclipsing star, which is probably the least massive (UX Ursae Majoris, $R = 0.3 \odot$, $M = 0.5 \odot$, $L = 1/40 \odot$) and the most massive eclipsing star (29 Canis Majoris, $R = 23 \odot$, $M = 40 \odot$, $L = 10{,}000 \odot$) conform to the same relation. Using Chandrasekhar's equations (54, 55) and a graph made in accordance with Tables I and II, we obtain the following results:

Star	R	M	L	μ	X	α	$f(\mu, X)$	ξ
	$\odot$	$\odot$	$\odot$					(Condensation)
UX UMa	0.3	0.5	$\frac{1}{40}$	1.0	0.4	0.0000	0.004	0.44
29 CMa	23.	40.	10^4	0.6	0.8	0.046	0.00005	0.80
				1.0		0.040	0.0003	0.80

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[20] B. Strömgren, Zs. f. Ap., 7, 224, 1933.
[21] S. Chandrasekhar, M.N., 96, 647, 1936.

which are in complete agreement with Chandrasekhar's values for seventeen other stars—the more massive stars (that is, the stars of early type in the main sequence) are more homogeneously built than the less massive stars. Giant eclipsing stars like 29 Canis Majoris (Class O7) tend to be very homogeneous, because the condensation is greater than 0.8. These results on condensation must be regarded, however, as only preliminary.[22]

Finally, we may mention the unique possibilities presented by eclipsing variables in the study of stellar atmospheres. At present such investigations have been confined to ζ Aurigae, but could no doubt be extended to other systems, for example, VV Cephei.[*]

23. The Additional Effects in Eclipsing Systems.—In earlier sections we have discussed the fundamental dimensions of eclipsing stars, such as radius, mass, mean density, luminosity, spectrum, and temperature. We shall now review the additional phenomena exhibited by these systems, the significance of which has only recently been realized, especially in their bearing on the internal constitution of the stars.

i. *The Ellipticity of the Components.*—The curvature of the light curve between minima represents chiefly the ellipticity of the components, or, in some cases, of one of the components. For about a hundred systems the ellipticity has been calculated from the light curve, and important conclusions can be drawn from this material. We consider first the ellipticity derived from the (U) solution (surface brightness has no darkening at the limb). The smallest values for the ratio b/a ($= \sqrt{1-\epsilon^2}$) are found for short-period eclipsing systems like W Ursae Majoris. But all of the short-period eclipsing systems do not show high ellipticity; for example, the eclipsing system of shortest known period, UX Ursae Majoris, has very small ellipticity of the components.

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[22] See H.C. 421, 1937.

[*] An unpublished result, obtained at Michigan by Goedicke, has recently confirmed this suggestion (Sept., 1938).

In a statistical study of 195 known eclipsing systems with periods less than a day, more than twenty-five per cent give no evidence of ellipticity. Some of these will probably be found, upon further examination, to show slight ellipticity, but there can be no doubt that the majority of them have no ellipticity. The mean value of *b/a* for 65 eclipsing stars is 0.90, and the average resultant decrease in brightness is about $0^m.13$.

There are four systems (π^5 Orionis, b Persei, π Cassiopeiae, ζ Andromedae) whose variations can be ascribed to the ellipticity alone, without recourse to eclipses, but they are all spectroscopic binaries. Hitherto no single star has been found that shows variations attributable to the rotation of a non-spherical body.

It is of interest to note that the so-called β Lyrae stars—stars with ellipticity like that of W Ursae Majoris, but with components that differ in surface brightness—are very numerous among the short-period eclipsing stars. One-half of all known β Lyrae stars (about a hundred are known) have periods of less than a day. As regards frequency of period, there is thus no very definite distinction between the β Lyrae and W Ursae Majoris types for periods less than a day, but the former tend to be brighter than the latter; their mean apparent magnitude is about 10, while that of the W Ursae Majoris stars is about 12. Probably the short-period β Lyrae stars are absolutely brighter than the W Ursae Majoris stars—a suggestion that is confirmed by a comparison of their spectra: the average spectrum for ten short-period β Lyrae stars is A5, and that for fifteen W Ursae Majoris stars is G0. Considering the Algol stars with periods less than 1^d (systems without ellipticity), we find for the spectra an average of F2. However, the spread of spectrum within these groups is large; thus, for the β Lyrae stars we have the limits CN Lacertae (G3) and SU Cephei (B8); for the W Ursae Majoris stars, RW Doradus (K5) and AG Virginis (A0); for the Algol stars, YY Geminorum (M1) and EZ Carinae (B8). Probably physically significant grouping would lead to some relation between type, period, and spectrum, even for periods less than a day. In spite of a considerable dispersion, the periods of the W Ursae

Majoris stars are evidently the shortest: of the fourteen stars with periods less than $0^d.3$, all except one are of W Ursae Majoris type; that is, they have the highest densities among the eclipsing stars. There appears to be here a fruitful field for discovering a physical relationship. It is difficult to understand the large differences in ellipticity within each period group; it is not only a matter of variation in the distance between the centers or the surfaces, for in all cases the components are near enough to make ellipticity probable. If there is a critical limit that distinguishes an Algol star from a W Ursae Majoris star, it must be observationally inconspicuous. Hitherto there has been no significant investigation of the problem of the evolution of eclipsing systems with periods less than a day, but there is little doubt that a careful study of all their properties will yield some information on the subject; probably the distinction between elliptical and non-elliptical stars will be found to have a deeper physical meaning.

It is well known that in a close eclipsing system with components of nearly equal surface brightness, the determinations of ellipticity and of duration of eclipse [or $1-(a_1+a_2)$] are badly entangled. A small ellipticity and long eclipse may be adjusted to give nearly the same light curve as a larger ellipticity and shorter eclipse. Very accurate observations are required to make the solution definite. The large differences in ellipticity, given in our table, for stars with the same value of (a_1+a_2), may arise from this cause, and individual study of the observations is necesary before the tabular differences can be accepted as real. We note as having abnormally small tabular ellipticity V Leporis and WZ Andromedae; abnormally great, RV Canum Venaticorum and VY Lacertae.

Taking means of the ellipticity data for the stars in Table II, XX, we find the following [grouped according to $1-(a_1+a_2)$]:

Number	7	7	9	8	8	7	9	7
Mean $1-(a_1+a_2)$	0.11	0.18	0.28	0.31	0.38	0.46	0.51	0.60
Mean b/a (U)	0.79	0.82	0.86	0.88	0.89	0.93	0.95	0.97

TABLE II, XX

ELLIPTICITY OF ECLIPSING SYSTEMS

Star	b/a (U)	b/a (D)	$1-(a_1+a_2)$	Spectrum
RT And	0.96	0.97	0.33	K2
WZ And	.97	.99	.28	A5
AA And	.77	.86	.22	A5
AB And	.73	.85	.16	G5
AD And	.94	.96	.28	F
AN And	.96	.92	.49	A7
S Ant	.75		.10	A8
RY Aqr	.95	.97	.56	A3
σ Aql	.96		.52	B3
SX Aur	.88		.28	B4
TT Aur	.79	.87	.41	B5
AH Aur	.80	.88	.29	(G0)
β Aur	.99	.99	.69	A0
SU Boo	.91	.95	.40	a5
TZ Boo	.79	.88	.15	(K0)
Y Cam	.93	.96	.51	A
SS Cam	.91	.94	.40	G5
RZ Cnc	.82	.90	.17	K0
RS CVn	.92?		.17	F4
RV CVn	.65	.81	.29	F8
R CMa	.97		.50	F0
X Car	.88?		.00	A
DW Car	.91	.94	.41	(F0)
EQ Car	.96	.98	.50	(G5)
RX Cas	.81	.88	.46	G8
RZ Cas	.97	.98	.51	A0
SX Cas	.85		.64	A6
TV Cas	.92	.95	.39	B9
XX Cas		.91	.40	B4
ZZ Cas	.96	.98	.40	(F5)
AO Cas	.96		.00	O8
RR Cen	.63	.68	.37	F2
RZ Cen	.90	.94	.28	B2
SV Cen	.75	.85	.27	B8
SZ Cen	.93	.96	.46	A2
U Cep	.97	.96	.48	A0
VW Cep	.69		.13	G5
WY Cep	.83		.20	(A7)
RW Com	.73	.84	.17	G4

TABLE II, XX—*Continued*

Star	b/a (U)	b/a (D)	$1-(a_1+a_2)$	Spectrum
RZ Com	0.86	0.92	0.31	(K0)
SS Com	.83	.90	.27	K0
U CrB	.97	.97	.56	B5
W Cru	.86	.91	.06	G0p
WZ Cyg	.84	.90	.17	A0
CG Cyg	.95	.96	.33	A4
DK Cyg	.78	.87	.18	(K0)
DL Cyg	.97	.98	.50	B3
RW Dor	.73?	.85?	.38	K5
Z Dra		.98	.51	A7
RZ Dra	.82	.89	.22	Ap
TW Dra	.97?		.47	A3
AC Gem	.91	.94	.37	(F0)
AH Gem	.85	.91	.32	(G8)
AI Gem	.95?		.31	(F0)
RX Her	.97	.99	.58	A0
u Her	.86	.90	.32	B3
RX Hya	.95		.31	A2
RT Lac	.95	.97	.36	G8
SS Lac	.90?	.94?	.35	A0
VY Lac	.75	.88	.36	(A2)
SW Lac		.81	.13	G2
AG Lac	.92	.95	.30	(F8)
V Lep	.95		.18	A5
δ Lib	.95		.39	A0
TT Lyr	.98		.58	A
β Lyr	.77	.75	.05	B8
TU Mon	.95	.98	.51	B8
UY Mon	.76	.87	.31	(F5)
TV Mus	.88?	.89?	.23	(G0)
Z Nor	.95	.97	.48	B5
U Oph	.91	.94	.50	B4
RV Oph	.96		.66	A3
CP Ori	.97	.98	.48	(B8)
U Peg	.77	.86	.10	F3
RT Per	.98	.99	.42	F0
AB Per	.96?	.98?	.45	A4
β Per	.96		.55	B8
V Pup	.81	.89	.13	B1
TY Pup	.81?	.90?	.44	F0
FV Sco	.96	.98	.58	B9
RT Scl	.80	.88	.12	A5
U Sct	.85	.90	.31	G5
RS Sct	.85	.91	.47	F
V Ser	.95	.97	.51	B8

TABLE II, XX—*Concluded*

Star	b/a (U)	b/a (D)	$1-(a_1+a_2)$	Spectrum
λ Tau	0.95		0.48	B3
V Tri	.88	0.93	.32	A1
X Tri	.93		.37	A3
W UMa	.75	.85	.26	F8p
W UMi	.94	.96	.28	A0
AG Vir	.69?	.83?	.14	A0
AH Vir	.86	.92	.28	K0
Z Vul	.87	.92	.43	B3
RS Vul	.98		.53	B8

For UX Ursae Majoris, $r_1 = 0.20$; $r_2 = 0.16$, or, in the other notation, $1-(a_1+a_2) = 0.64$. Hence the ellipticity to be anticipated is of the order of 0.97, and it is no wonder it has not been observed.

The critical limit which distinguishes an Algol star from a W Ursae Majoris star must be an approximate value of (a_1+a_2); there is no sharp limit, in the nature of the case.

There are three phenomena, noticeable in the light curve, that arise from the eccentricity of the orbit: the displacement of the minima; the difference in duration of first and second eclipses; and the different shapes of the minima. The first of these effects is the most conspicuous, the third is the least so, and therefore the majority of eccentricities have been determined from displacements of the minima. Nevertheless there have been attempts, notably by Krat, who, with his collaborators at Kasan, has given quantitative information and developed necessary formulae, to use the shape of the minimum in deriving eccentricity.

Finally, we shall consider the relative numbers of elliptical and non-elliptical systems of short period. The discovery-chance for an eclipsing system depends chiefly on the ratio of the sum of the radii to the distance between the centers. The sum of the radii for elliptical stars is on the average about 1.5 times as large as for non-elliptical stars; if we take the ellipticity rigorously into account, the ratio becomes 1.4. Thus the number of known elliptical systems ought to be larger than that of non-elliptical systems, roughly in this proportion. Why then does observation show that the actual number of non-elliptical stars is about twice as great as that of elliptical stars? Probably the most important reason is that the establishment of an elliptical system by observation is more difficult than that of a non-elliptical system. Secondly, there is among the non-elliptical systems a large percentage of A stars, generally associated with large differences of spectrum and luminosity between the components, which are statistically connected with small ellipticity. If a cosmological cause is to be found for the apparent deficiency of elliptical systems it will be necessary to extend considerably our knowledge concerning the evolution of eclipsing systems, and double stars in general—a region of knowledge at present confined to the realms of speculation.

ii. *Eccentricity.*—Almost all the eccentricities given in Table II, XXI, are derived from spectroscopic observations, and it is known that this method for determining eccentricities less than 0.1 is not as adequate as photometric observations. There are fourteen systems with eccentricity equal to or larger than 0.10: ϵ Aur (0.35), ζ Aur (0.41), AR Cas (0.22), VV Cep (0.25), R CMa (0.14), α CrB (0.39), RW CrB (0.12), Y Cyg (0.178), MR Cyg (0.12), RU Mon (0.38), WZ Oph (0.10), δ Ori (0.11), WY Sgr (0.37), β Sco (0.27), TX UMa (0.188), AG Vir (0.10). Of these, the values for RU Mon and WY Sgr have been established photometrically. There is very little doubt that all except those for δ Ori, WZ Oph, and possibly for MR Cyg, are real; in other words, there are only eleven eclipsing binaries for which the eccentricities are spectroscopically determined. Many of these latter systems (ϵ Aur, ζ Aur, VV Cep, α CrB) cannot be tested photometrically; the rest, however, can be, and for R CMa and Y Cyg the eccentricity has been shown photometrically to be real.

In the year 1937 two eclipsing variables were discovered, for which photometric observations lead to the highest eccentricities ever found for eclipsing variables.

TABLE II, XXI

ECCENTRICITY OF ORBITS OF ECLIPSING SYSTEMS

Star	*e*	ω	*P*	Spectrum
			d	
AN And	0.036(0.00)(ph)		3.22	A7
AP And	.026(ph)	277.8	1.58	
TT Aur	.048	262.3	1.33	B5
ε Aur	.350?	319.7	9900	cF5
ζ Aur	.411	330.1	972.2	K5 + B8
X Car	.02	165	1.08	A0
RZ Cas	.052	155	1.20	A0
TV Cas	.01		1.81	A0 + A0
TW Cas	.08	277	2.86	B9
AO Cas	.040	210	3.52	O8 + O8
AR Cas	.22	30	6.07	B3
CC Cas	.10	300.8	3.37	O8 + O8
VV Cep	.25		7430	M2 + B9
RT Cen	.22		4.13	
R CMa	.138?	196	1.14	A9
U CrB	.07(sp)	23	3.45	B3 + B3
RW CrB	.12	160	0.73	A8
α CrB	.39	138	17.36	A0
W Cru	.040		198.5	G0
Y Cyg	.178		3.00	O9 + O9
MR Cyg	.12		1.68	A0 + A0
Z Dra	.01	270	1.36	A5
TW Dra	.054	90	2.81	A3
AK Her	.00		0.42	F8
u Her	.051	67	2.05	B3 + B3
RX Hya	.032	180	4.56	A2
δ Lib	.054?	29	2.33	A0
RR Lyn	.081	153	9.94	A3
β Lyr	.018		12.91	B8 + B5
RU Mon	.383		3.58	A
WZ Oph	.10		4.18	G0 + G0
δ Ori	.110	338	5.73	B1
η Ori	.016	42.3	7.99	B3
RT Per	.012(0.044ph)	90(73.6)	0.85	F
AG Per	.047(ph) 0.051(sp)	44.5(30.10)	2.03	B3 + B3
β Per	.038	278	2.87	B8
V Pup	.080		1.45	B1 + B3
U Sge	.035	44	3.38	B9 + G2
RS Sgr	.091	261	2.42	A0
WY Sgr	.368?		4.67	B9

TABLE II, XXI—*Concluded*

Star	e	ω	P	Spectrum
			d	
β Sco	.270	20	6.83	B0
μ Sco	.050	190	1.45	B3 + B3
RW Tau	.041?		2.77	A0
λ Tau	.061	75	3.95	B3
W UMa	.00		0.33	F8 + F8
TX UMa	.188		3.06	B9 + A3
AG Vir	.10	90	0.64	A0
α Vir	.01	328	4.01	B3
Z Vul	.05	274	2.45	B3 + B3
RS Vul	.053	236	4.48	B8 + B9

iii. *Apsidal Motion and Libration.*—The apsidal motions (motion of periastron) are probably the most striking and attractive phenomena among eclipsing stars. Among the three possible causes of apsidal motion (flattening of the components by rotation, effect of a third body, and relativity term; the two latter are very small and are still not well established for any eclipsing binaries), the best understood rôle is that played by flattening. In addition to the effects mentioned, another, affecting the light curve, namely libration, has been discussed by Walter.[23]

iv. *Rotation Effect.*—The width of a line in the spectrum of a rotating star depends on the size of the surface presented to the observer. During an eclipse that is total or nearly so, the light comes only from a part of the surface with a consequent smaller range of velocities; thus the "center of gravity" of the line will be shifted, and the line will appear displaced and asymmetrical. The effect will be largest if the luminosity of the eclipsed star is nearly equal to that of the whole system, and if the inclination be nearly 90°; the size of the effect depends of course on the velocity of the rotation—that is, on the period. It can be discovered only spectroscopically. If both spectra are visible, the rotation effect should be observed in both, but such data are not available for any system. The phenomenon has been observed with greater or less precision in half a dozen systems (including Algol and λ Tauri), but the results of different observers are not always consistent. Further observations will be of great importance.

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[23] Walter, Publ. Königsberg Obs., 2, 1933; 3, 1934.

The rotation effect gives important independent information concerning the sizes of the components in an eclipsing system, on the assumption (always made) that the rotation and revolution times are equal. It is not yet possible to decide whether the sizes determined by the several methods are in satisfactory agreement.

v. *Reflection Effect.*—The best theoretical expression of the reflection effect involves, according to Krat, a function of $\sin^n x$, where x is the phase, and n is about 4. The reflection effect has several influences on the elements of an eclipsing system. First, it may change the apparent spectrum of the second component; secondly, it produces a change of brightness between the minima, so that the reflection effect works with the effect of ellipticity of components in distorting the light curve. If the orbit is eccentric the reflection effect will be combined with any periastron effect that may be present. Fortunately the reflection effect is small, and the effect of ellipticity can usually be well separated from it. Thirdly, the reflection effect may influence the computed absolute dimensions of the system, chiefly the masses, because the center of gravity of the observed light of each component is slightly displaced toward the other component, so that the apparent motion is diminished, and the deduced masses are a little too small. The reflection effect has been observed in about twenty-five eclipsing systems; the maximum observed value is about $0^m.05$, and the average observed value for stars known to show a reflection effect is $0^m.02$.

vi. *Darkening at the Limb.*—Limb darkening is empirically taken into account in the derivation of the photometric elements. The formula most often used is that derived for the sun.

vii. *The "Tikhoff-Nordmann" Effect.*—The shift in time of minimum for different colors was first observed, more than twenty years ago, by Tikhoff. The effect seems to be established for more than twenty stars; for most stars primary minimum curves occurs earlier in yellow than in blue light; but in the light curves of Algol, WW Aurigae, RZ Cassiopeiae, and (probably) OO Aquilae, the displacement is in the opposite direction. The most suggestive hypothesis that has been advanced to account for the effect is that given by Mustel, according to whom it may be explained in terms of tidal distortion and of the difference between the periods of rotation and revolution. The effect is found to be largest for the eclipsing stars of largest mass. For stars of short period, such as W Ursae Majoris, the effect, even if present, would be scarcely detectable.

24. The Catalogue of Relative Elements for 268 Eclipsing Systems.—The first catalogue of photometric elements by Shapley contained data for 90 eclipsing systems.[24] The second catalogue by Gaposchkin listed all eclipsing systems for which the elements had been computed up to 1932.[25]

There are now over 250 eclipsing systems for which the elements have been computed. For some systems several computations, based on different light curves, have been made, sometimes as many as ten. For most of the stars both uniform and darkened solutions have been carried out. We are thus confronted with a huge and varied amount of material in forming a catalogue. How should a solution be chosen? Probably the best method would be to combine all the elements for one star by using weights. We have limited ourselves to one solution for each system, preferably the darkened one. Other solutions are mentioned in the remarks.

One of the most important things to know about the elements is their accuracy. If both minima are well observed and sufficiently deep ($\overline{7}\,0^{m}.5$ after the rectification), then the computed elements should be fairly reliable. When the primary eclipse is total or annular, and a secondary minimum is also observed, then with a good light curve the elements will have high accuracy. In all other cases the derivation of elements presents difficulties. For some eclipsing systems the spectroscopic observations may be instructive, yet the derivation of the photometric elements should be carried out quite independently.

[24] Princeton Contr. No. 3, 1915.
[25] Veröff.Ber.-Bab., 9, Part 5, 1932.

The catalogue of elements is arranged as follows:

Star: name and constellation; italics refer to stars spectroscopically observed. See Table II, XXIII.

A_1; A_2: the observed ranges, the fundamental data for the relative elements; the apparent brightness of the system is not given, since it is not important in determining the physical properties of the star (except in some cases). Where ellipticity has been deduced, the ratio b/a is given in the remarks.

Ecl.: type of primary eclipse. The symbols t, a, tp, ap and p denote respectively: total, annular, total-partial (larger star in front), annular-partial (smaller star in front), and partial (both components equal).

Per.: period of revolution, in days.

L_b: relative total luminosity of the brighter component, in units of the system. The conception of "brighter" refers to the total luminosity, not to the surface brightness. The relative total luminosity is immediately known only if the eclipse is total. The relative surface brightness is known in all cases where the two minima are observed.

r_b: radius of the brighter component, in units of the distance between the centers.

k: the ratio of radii, always given in the sense, brighter/fainter. In most cases k is less than 1.0, but when the brighter is also the larger, k is greater than 1.

i: the inclination of the orbit.

γ: ratio of surface brightness (brighter/fainter).

Sol.: type of solution, U= uniform, D = darkened.

b/a: ratio of semi-axis minor to semi-axis major, for darkened (D) and uniform (U) solutions.

Quality: degree of accuracy. In many cases the evaluation was difficult; we have attempted to give the most probable elements, and an estimate of their acceptability. The symbol I means that the orbit is of the first class—deep minima and an accurate light curve. The symbol Ia indicates that though the minima are deep enough, the light curve is still not well observed. The symbol II indicates that the elements are of the second class, either because the minima are too shallow, or because the observations are not complete enough; these elements may still be of considerable accuracy, comparable to Class Ia. The symbol IIa means that the elements are uncertain. The symbol III means that the elements are only rough approximations; IIIa, that they are very uncertain in respect to the light curve. It may happen that our ratings for some stars are too low, but it is preferable to suggest that a star needs further observation than to indicate that its case is closed.

Sp_b: spectrum of the brighter component, observed. In a few cases in which no spectrum is known, we indicate a probable spectrum, derived from period and apparent magnitude; such spectra are given in parentheses.

Sp_f: spectrum of the fainter component; the observed ones are given without parentheses. The spectra computed from the relative surface brightness are given in parentheses. Most of the computed spectra are taken from the elements by Gaposchkin.

Reference to authority for the elements; references are given at the end of the catalogue. The symbol G refers to unpublished Harvard work by S. Gaposchkin.

TABLE II, XXII

RELATIVE ELEMENTS OF ECLIPSING STARS (MARCH, 1938)

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a D	b/a U	Quality	Sp_b	Sp_f	Reference
	m	*m*		*d*				°								
RT And	0.96	0.30	t	0.629	0.54	0.28	0.75	84.2	2.1	D	0.97	0.96	Ia	K2	(K8)	25, 94
SY And	1.50	(0.01)	t	34.91	0.75	0.02	0.13	81.0	178.	0.4D			Ia	A0	(K0)	18, 70
TT And	1.30	(0.10)	t	2.766	0.80	0.18	0.70	81.9	8.4	D			Ia	A	(F5)	70, 25
TW And	1.65	(0.02)	t	4.123	0.78	0.17	0.69	86.0	17.7	D			I	A0	(G0)	72
UU And	2.95	(0.04)	t	1.486	0.93	0.34	0.88	87.8	18.0	D			I	(A0)	(F7)	19
WW And	1.10	—	t	23.29	0.64	0.08	0.75	89.3	3.1	D			I	A5	F3p	99, 25
WZ And	1.70	0.12	t	0.696	0.79	0.33	0.78	84.8	6.1	D	0.97	0.99	II	A5	(F6)	25
AA And	1.21	0.29	p	0.935	0.69	0.39	1.00	82.3	2.3	D	0.86	0.77	II	A5	(F3)	25
AB And	0.95	0.85	p	0.332	0.52	0.42	1.00	86.1	1.1	U	0.85	0.73	Ia	G5	(G6)	25
AD And	0.95	0.72	t	0.987	0.54	0.36	0.99	89.9	1.2	U	0.96	0.94	II	F	(F1)	25
AN And	0.11	0.04	ap	3.220	0.80	0.36	2.27	69.8	—	D	0.98	0.95	III	A7s	Ap	54, 25
AP And	0.62	0.62	tp	1.587	0.53	0.12	0.94*	89.1*	1.00	U			II	—	—	37, 54
S Ant	0.44	0.40	ap	0.648	0.67	0.50	1.30	62.2	1.2	U		0.75	II	A8	A8	32
RV Aps	4.6	—	t	34.07	0.98	0.12	0.50	86.0	196.	—			III	—	—	G
RY Aqr	1.31	0.11	tp	1.966	0.90	0.21	0.86	82.2	12.4	D	0.96	0.97	I	A3	(G5)	7,54
AY Aqr	1.0	0.6	ap	0.282	0.52	0.26	0.81	80.0	2.0	U			II	—	—	G
FK Aql	2.7	0.14	t	2.651	0.92	0.25	0.75	85.0	20.0	U			II	A3	—	G
OO Aql	0.86	0.74	ap	0.506	0.67	0.52	0.62	81.2	0.8	U			I	G5	(G6)	23
σ Aql	0.18	0.14	p	1.950	0.57	0.24	1.00	71.7	1.3	U		0.96	II	B8	B8	98
RW Ara	1.91	—	t	4.367	0.83	0.11	0.30	75.7	53.4	D			I	A0	(K0)	73
UW Ara	0.90	0.10	tp	3.297	0.71	0.21	0.62	84.1	6.5	D			II	A0	(F3)	25
RS Ari	1.30	—	t	8.803	0.70	0.04	0.31	—	23.0	—			IIIa	F9	G5	51a, 99
RZ Aur	1.74	—	t	3.011	0.80	0.26	0.97	90.0	4.2	D			II	A	(F1)	70
SX Aur†	0.76	0.46	ap	1.210	0.71	0.48	1.25	80.7	1.6	U		0.88	IIa	B4	—	99, 25, 56
TT Aur‡	0.96	0.37	ap	1.333	0.68	0.38	1.11	87.1	0.32	U		0.84	I	B3	B3	33, 25, 70

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a		Quality	Sp_b	Sp_f	Reference
											D	U				
	m	*m*		*d*				°								
WW Aur	0.66	0.54	ap	2.525	0.56	0.18	1.05	87.7	1.2	U			I	A7	A7	7
AH Aur	0.46	0.42	tp	0.494	0.54	0.34	0.85	73.5	1.2	D	0.88	0.80	II	F8	(G1)	25
AK Aur	0.56	0.06	tp	7.146	0.74	0.08	0.52	81.6	10.5	D			II	B9	(F8)	25
AM Aur	1.52	0.11	t	13.62	0.75	0.25	0.60	82.0	8.5	U			II	A5	(G5)	G
AR Aur	0.71	0.52	tp	4.134	0.51	0.10	0.92	88.1	1.2	U			Ia	B9	A0	53
β *Aur*	0.09	0.09	p	3.96	0.50	0.16	1.00	77.0	1.0	D	0.99		II	A1	A1	70, 54
ε *Aur*	0.80	—	t	9888.	0.52	0.03	0.10	75.2	100.	U			Ia	F5p	(K5)	30, 70, 25
ζ *Aur*§	0.70	—	t	972.	0.50	0.20	73.	80.8	5330^{-1}	U			Ia	K5	B9	30a
SS Boo	0.40	0.06	a	7.605	0.95	0.15	1.67	90.0	6.3	D			III	a6	(G2)	66
SU Boo	0.50	0.11	ap	1.561	0.93	0.34	1.28	77.0	3.5	D			IIa	—	—	25
TZ Boo	0.50	0.45	p	0.297	0.55	0.43	1.00	79.7	1.2	U	0.88	0.79	II	(K0)	(K2)	25
i Boo	0.42	0.42	p	0.268	0.50	0.37	1.00	62.0	1.00	U			Ia	G2	G2	G
Y Cam	1.68	0.10	t	3.306	0.79	0.19	0.83	90.0	5.4	0.3D			Ia	A	(F3)	19, 70, 7, 74
SS Cam	0.57	0.15	a	4.824	0.64	0.44	2.78	76.0	5.0	D	0.94	0.91	Ia	G1	F5	50
SV Cam	0.64	0.05	tp	0.593	0.50	0.18	0.50	81.1	3.8	U			II	G5	G3	15, 57
S Cnc	2.12	(0.05)	t	9.485	0.86	0.10	0.52	85.2	22.0	D			Ia	A0	G5	70, 19
RU Cnc	1.55	(0.03)	t	10.17	0.76	0.06	0.30	84.5	35.0	D			Ia	F9	G9	70, 19, 99
RY Cnc	2.80	—	t	1.09	0.92	0.24	0.83	86.6	17.5	U			II	—	—	29
RZ Cnc	1.64	0.26	t	21.64	0.71	0.24	0.48	78.5	11.0	D			Ia	K0	K4	25
TU Cnc	2.90	—	t	5.561	0.93	0.14	0.70	88.0	26.0	U			II	—	—	G
RS CVn	1.91	0.08	t	4.798	0.83	0.13	0.64	90.0	11.7	U			II	F4	G8	82, 67, 68
RV CVn	0.77	0.60	tp	0.270	0.58	0.36	0.97	81.0	1.4	U			II	F8	(G1)	G
R CMa	0.56	0.06	ap	1.136	0.93	0.25	1.02	76.6	12.2	U			Ia	F0	(K3)	7
UW CMa	0.33	0.32	ap	4.393	0.60	0.44	1.20	68.3	1.0	U			II	O9	O9	26
RY CMi	3.0	0.05	t	3.265	0.94	0.15	0.60	90.0	47.0	U			II	—	—	G

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a D	b/a U	Quality	Sp_b	Sp_f	Reference
	m	*m*		*d*				°								
RW Cap	1.45	0.24	p	3.392	0.79	0.23	1.00	87.4	3.7	D			II	A3	A4	70
X Car	0.8	—	p	1.083	0.52	0.50	1.00	84.5	1.1	U			III	A0	(A1)	70
SS Car	0.66	0.66	tp	6.602	0.54	0.11	0.92	89.4	1.0	U			IIa	A	(A)	70
ST Car	0.88	0.06	tp	0.902	0.87	0.29	0.80	73.8	10.3	D			I	A0	(F6)	70
CI Car	1.10	0.11	t	2.818	0.60	0.13	0.70	86.7	3.1	—			II	—	—	25
CV Car	1.70	0.03	t	14.42	0.79	0.09	0.30	84.9	34.4	—			II	—	—	25
CZ Car	0.90	0.11	t	2.285	0.79	0.14	0.70	86.6	5.0	—			II	—	—	25
DK Car	0.96	0.01	t	11.33	0.59	0.06	0.25	90.0	23.0	—			II	—	—	25
DM Car	1.84	0.0	t	5.316	0.82	0.10	0.50	89.0	17.0	—			II	—	—	25
DP Car	1.00	0.10	t	7.564	0.60	0.11	0.50	90.0	6.0	U			II	A8	(G1)	34
DW Car	0.50	0.50	ap	1.328	0.53	0.33	1.25	81.5	1.0	D	0.94	0.91	II	—	—	25
EQ Car	1.05	0.07	t	25.52	0.97	0.20	0.75	85.0	18.0	D	0.98	0.96	Ia	(G5)	(M5)	25
FP Car	1.70	0.08	t	176.03	0.78	0.03	0.58	89.8	10.6	U			Ia	A5	(G0)	75
FS Car	0.51	0.51	p	2.147	0.50	0.34	1.00	83.3	1.0	U			II	—	—	25
RX Cas	0.69	0.55	p	32.32	0.57	0.28	1.00	81.0	1.3	D	0.88	0.81	IIa	G2p	(G4)	70
RZ Cas	1.59	0.06	ap	1.195	0.92	0.28	0.96	81.6	12.3	D	0.99	0.98	I	A2	(G3)	9, 70, 25, 87, 16
SX Cas	0.99	0.32	a	36.57	0.54	0.25	2.12	88.3	5.3	U		0.85	I	A6	G6	10, 70, 25
TX Cas	0.55	0.32	ap	2.927	0.83	0.57	1.95	87.0	1.3	D			Ia	A0	(A3)	51
TV Cas	1.05	0.09	tp	1.813	0.84	0.29	0.88	74.2	7.0	D			I	B9	(F5)	51, 70, 25, 16
TW Cas	0.62	0.57	p	2.857	0.58	0.16	1.00	86.8	1.4	D			I	B9	(A2)	51
XX Cas	0.85	0.30	ap	3.067	0.80	0.36	1.57	83.7	1.9	D	0.91		Ia	B4	B6:	58
YZ Cas	0.70	0.07	a	4.467	0.94	0.16	2.04	87.4	3.5	D			Ia	A3	(F2)	35, 41
ZZ Cas	0.50	0.22	tp	1.243	0.56	0.26	0.75	76.7	2.4	U			II	—	—	25
AB Cas	1.95	—	tp	1.367	0.96	0.18	0.85	85.5	31.0	U			I	A3	—	37
AO Cas	0.19	0.19	tp	3.523	0.74	0.61	1.52	51.8	1.2	U			III	O8.5	O8.5	58

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a		Quality	Sp_b	Sp_f	Reference
											D	U				
	m	*m*		*d*				°								
AR Cas	0.13	0.03	tp	6.066	0.97	0.19	2.86	84.5	3.9	D			IIIa	B3	(A4)	88
RR Cen	0.26	0.26	a	0.606	0.94	0.5	4.16	74.8	1.0	U			II	F2	(F2)	37
RZ Cen	0.46	0.34	a	1.876	0.82	0.49	2.09	90.0	1.2	D			Ia	B2	(B3)	70
SS Cen	1.55	—	tp	2.479	0.94	0.17	0.64	80.3	30.	U			Ia	B9	(G3)	70
SU Cen	0.87	0.06	ap	5.354	0.93	0.25	1.19	82.2	10.0	D			II	F5	(K2)	70
SV Cen	0.86	0.26	ap	1.661	0.77	0.37	1.19	82.0	4.7	D			Ia	B8	(A7)	70, 25
SW Cen	2.33	—	t	5.219	0.88	0.10	0.44	90.0	36.0	D			Ia	A0	(G5)	70
SY Cen	0.87	—	tp	6.631	0.79	0.18	0.40	67.0	33.0	D			IIa	A	(K0)	70
SZ Cen	0.65	0.59	ap	4.108	0.59	0.30	1.42	83.1	1.1	D			Ia	A2	(A3)	70
WZ Cen	1.10	0.70	t	3.612	0.75	0.40	1.00	87.0	3.0	U			II	—	—	G
AB Cen	2.60	—	t	46.85	0.91	0.04	0.20	88.5	275.	U			II	—	—	G
BH Cen	1.0	1.0	p	0.79	0.52	0.35	1.00	89.0	1.0	U			Ia	—	—	G
KT Cen	0.45	0.45	ap	4.130	0.65	0.16	1.40	86.9	1.0	D			I	—	—	42
OX Cen	1.10	0.6	t	0.467	0.64	0.37	1.00	90.0	1.9	—			II	—	—	G
U Cep	2.66	0.04	t	2.493	0.84	0.20	0.62	86.4	13.5	0.6D			I	A0	G8	11, 70, 25, 16
RS Cep	1.66	—	t	12.420	0.78	0.08	0.41	88.5	22.0	D			Ia	A	(G2)	70
VV Cep	0.80	—	t	7430.	0.52	0.36	100.	72.0	10^{-4}	U			II	M2	B9	27
VW Cep	0.35	0.26	ap	0.278	0.60	0.51	1.44	50.3	—	U		0.69	Ia	G5	—	10
WY Cep	0.88	0.71	tp	1.249	0.52	0.39	0.95	82.0	1.2	U			Ia	A7	(A9)	83
XZ Cep	0.81	0.17	t	5.096	0.52	0.09	0.50	85.1	4.3	U			Ia	B5	(A2)	83
AH Cep	0.22	0.13	tp	1.775	0.60	0.35	0.75	66.8	0.9	U			Ia	B0	B0	101
SS Cet	3.20	—	t	2.974	0.95	0.10	0.64	90.0	50.0	U			II	—	—	G
T Cir	0.88	0.01	t	3.298	0.80	0.27	0.80	78.7	6.3	D			II	B9	(F6)	25
RW Com	0.67	0.67	tp	0.237	0.55	0.40	0.90	80.1	1.0	D	0.84	0.74	Ia	—	—	25
RZ Com	0.60	0.60	p	0.339	0.50	0.34	1.00	80.8	1.0	U		0.92	Ia	(K0)	(K0)	25

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a D	b/a U	Quality	Sp_b	Sp_f	Reference
	m	*m*		*d*				°								
SS Com	0.79	0.79	p	0.413	0.50	0.37	1.00	84.1	1.0	U		0.83	Ia	(K0)	(K0)	25
BG CrA	0.90	0.70	p	0.453	0.60	0.30	1.00	87.0	1.2	U			Ia	(K0)	(K2)	G
U CrB	1.02	(0.01)	tp	3.452	0.76	0.10	0.26	68.4	50.0	D			Ia	B5	B9	19, 70, 25
RW CrB	0.54	0.03	ap	0.726	0.97	0.39	1.03	78.4	12.7	D			Ia	F8	—	58
α CrB	0.11	—	ap	17.36	1.00	0.05	3.58	90.0	∞	0.5D			II	A0	—	89, 39
W Cru	0.60	0.28	a	198.5	0.90	0.61	0.56	76.0	3.0	D	0.91	0.86	Ia	G0p	(G4)	60, 56a
Y Cyg	0.60	0.40	p	2.996	0.58	0.17	1.00	85.0	1.4	D			Ia	O9	O9	70
SW Cyg	2.66	—	t	4.573	0.91	0.17	0.65	87.0	24.0	D			Ia	A2	(G9)	70, 20
SY Cyg	2.30	—	t	6.006	0.88	0.10	0.43	90.0	42.0	D			Ia	A	(K2)	70, 21
UW Cyg	2.28	—	t	3.451	0.88	0.19	0.84	90.0	10.0	D			Ia	A?	(F9)	19, 70
UZ Cyg	1.88	—	t	31.31	0.82	0.08	0.50	90.0	18.5	D			II	A3	K1	70
VV Cyg	0.75	—	ap	1.477	0.87	0.25	1.12	80.7	5.5	D			IIa	—	—	70
VW Cyg	1.94	—	t	8.430	0.83	0.12	0.54	90.0	17.0	D			II	A0	(F6)	70, 19
WW Cyg	3.67	—	t	3.318	0.97	0.17	0.58	82.0	86.0	D			Ia	A2	(K4)	18, 70, 25
WZ Cyg	1.45	0.44	a	0.584	0.79	0.47	1.28	85.0	2.4	D			I	A0	(A8)	70, 20
ZZ Cyg	1.09	0.06	tp	0.629	0.92	0.33	0.93	77.0	13.0	D			Ia	A	(G2)	70
AE Cyg	0.77	—	tp	0.969	0.50	0.31	0.75	85.0	1.3	—			III	A5	(A9)	71
BR Cyg	1.31	0.06	t	1.333	0.70	0.23	0.52	78.9	8.7	D			Ia	—	—	25
CG Cyg	1.12	0.33	tp	0.631	0.66	0.29	0.78	82.3	3.1	D	0.96	0.95	II	A4	(F1)	4
DK Cyg	0.61	0.55	tp	0.471	0.55	0.35	0.78	77.2	1.3	D	0.87	0.78	Ia	(G0)	(G2)	25
DL Cyg	0.69	0.17	tp	4.830	0.73	0.24	0.89	81.3	3.5	D	0.98	0.97	Ia	B3	(A8)	25
GO *Cyg*	0.61	0.26	tp	0.718	0.95	0.33	0.76	58.0	24.0	D	0.84		II	B9	A0	37, 47
KR Cyg	0.65	0.14	a	0.845	0.88	0.28:	1.39	85.5	3.9	U			Ia	—	—	45
MR Cyg	0.71	0.16	a	1.677	0.87	0.34	1.47	83.8	3.2	D			I	A0	A0	31, 37, 55
LO Cyg	0.80	0.27	ap	0.629	0.98	0.62	1.67	71.6	(16.0)	D			I	—	—	55

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a D	b/a U	Quality	Sp_b	Sp_f	Reference
	m	*m*		*d*				°								
V346 Cyg	1.16	0.28	t	2.743	0.65	0.28	0.77	89.7	3.1	U			Ia	—	—	22
W Del	2.70	—	t	4.806	0.92	0.17	0.71	86.0	22.0	D			Ia	A	(G7)	70, 61, 18
RR Del	1.20	—	t	4.599	0.67	0.11	0.45	82.6	9.6	U_2			Ia	A	(G5)	70, 21
RW Dor	0.60	0.45	p	0.285	0.67	0.32	1.00	80.0	1.9	U_2	0.85	0.73	Ia	M0	(M2)	25
Z Dra	2.55	0.07	tp	1.357	0.93	0.26	0.98	86.9	13.1	D	0.99		I	A5	(G7)	70, 62, 18, 12
RR Dra	2.96	—	t	2.831	0.93	0.13	0.58	85.6	42.0	D			Ia	A2	(K3)	70, 18
RX Dra	0.50	0.50	ap	3.786	0.63	0.11	1.28	88.6	1.0	U			Ia	F	(F)	70
RZ Dra	0.80	0.22	tp	0.551	0.90	0.34	0.77	72.0	15.0	U			III	F	(K4)	70, 49
SX Dra	2.08	—	t	5.169	0.85	0.10	0.25	72.5	93.0	D			Ia	A7	(K4)	18, 59
TW Dra	2.55	0.08	t	2.807	0.89	0.21	0.65	85.6	19.9	U		0.97	I	A6	K2	1, 70, 25
S Equ	2.22	0.04	t	3.436	0.96	0.11	0.90	90.0	24.0	D			Ia	A0	(G2)	37, 25
RZ Eri	1.20	0.20	t	39.28	0.67	0.07	0.75	88.5	3.5	U			II	A5	(F7)	25
RW Gem	1.98	0.11	t	2.865	0.84	0.21	0.73	90.0	10.0	0.9D			I	A	(F9)	18, 70
RY Gem	1.98	—	t	9.301	0.84	0.11	0.45	83.1	26.0	D			Ia	A3	(K3)	99, 25
YY Gem	0.60	0.60	ap	0.814	0.55	0.20	1.12	86.4	1.0?	D			II	M1	M1	32
AC Gem	0.60	0.45	tp	9.970	0.63	0.25	0.65	83.7	1.4	D	0.94	0.91	Ia	—	—	25
AF Gem	1.10	0.07	ap	1.244	0.75	0.39	1.12	78.4	2.8	D			Ia	—	—	25
AH Gem	0.50	0.50	p	0.337	0.50	0.35	1.00	79.9	1.0	D	0.91	0.85	IIa	—	—	25
AI Gem	0.35	0.30	p	0.725	0.53	0.35	1.00	71.8	1.2	U		0.95	Ia	—	—	25
U Gru	3.00	—	t	1.880	0.94	0.25	1.00	90.0	16.0	U			II	A5	—	81a
Z Her	0.80	0.13	tp	3.993	0.57	0.12	0.54	82.0	4.5	D			Ia	F2	F2	70, 20
RX Her	0.48	0.48	p	1.779	0.50	0.20	1.00	82.7	1.0	D			Ia	A0	A0	70, 25
SZ Her	1.83	0.24	tp	0.818	0.80	0.33	0.96	88.4	4.3	U			I	—	—	7, 70
TU Her	2.81	0.02	t	2.267	0.93	0.19	0.71	86.4	24.0	D			Ia	A	(G8)	19, 25
TX Her	0.70	0.34	p	2.060	0.64	0.15	1.00	86.6	1.8	U			Ia	A2	A2	2, 25

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a D	b/a U	Quality	Sp_b	Sp_f	Reference
	m	*m*		*d*				°								
AD Her	2.20	—	t	9.767	0.87	0.09	0.62	88.5	20.0	U			Ia	A4	K2	G
AK Her	0.62	0.44	ap	0.426	0.58	0.36	1.21	85.2	1.1	—			II	F8	(G5)	25
u Her	0.64	0.28	ap	2.051	0.54	0.40	1.67	76.1	—	D			Ia	B3	B3	3, 70, 25
RX Hya	2.69	0.05	tp	2.282	0.93	0.20	0.79	85.6	20.0	—			II	A2	(K0)	13
SX Hya	4.06	—	t	2.896	0.96	0.13	0.50	82.5	110.0	D			I	A3	(K)	76
TT Hya	2.45	0.01	t	6.954	0.89	0.07	0.31	82.6	95.0	D			Ia	A2	G6	75
RT Hyi	0.90	0.90	ap	0.284	0.52	0.36	1.06	89.2	1.0	U		0.84	II	(K0)	(K0)	G
RT Lac	1.06	0.61	t	5.074	0.60	0.29	1.00	90.0	1.5	D	0.97	0.95	II	G9	K1	70, 24
SS Lac	0.50	0.50	tp	14.42	0.68	0.06	0.68	90.0	1.0	U			II	A	(A)	97
SW Lac	0.82	0.68	tp	0.321	0.54	0.42	0.93	73.0	1.4	D	0.81		II	G3	G3	64
UW Lac	0.92	0.05	ap	5.290	0.98	0.35	1.41	84.3	24.0	D			II	—	—	25
VY Lac	0.95	0.36	p	1.036	0.88	0.32	1.00	81.0	7.4	D	0.88	0.75	Ia	A2	(F8)	25
AG Lac	1.40	0.40	t	0.752	0.70	0.31	0.90	90.0	2.8	D	0.95	0.92	Ia	—	—	25
AR Lac	1.11	0.11	tp	1.983	0.71	0.18	0.62	79.1	6.5	U			Ia	K0	G5	25, 85
CM Lac	1.03	0.29	tp	1.604	0.62	0.15	0.80	87.2	2.6	D			Ia	A2	A8	96
CN Lac	0.50	0.14	ap	0.637	0.95	0.36	1.14	77.5	(14.0)	D			Ia	G3	—	55
Y Leo	2.97	0.05	t	1.686	0.93	0.25	0.85	88.1	20.0	U			Ia	A	(G6)	77, 70, 19
RW Leo	1.50	0.00	t	1.683	0.75	0.15	0.70	86.4	6.1	D			Ia	—	—	25, 69
T LMi	2.48	0.04	tp	3.020	0.96	0.22	0.93	86.7	28.2	D			I	A5	(K3)	51
V Lep	0.73	0.25	ap	1.070	0.80	0.48	1.39	79.0	2.1	D	0.97		I	A5	(A9)	78
δ *Lib*	1.10	0.05	ap	2.327	0.95	0.39	1.33	84.2	11.0	D			II	A0	(G0)	70, 41
RV Lyr	2.36	—	tp	3.599	0.89	0.14	0.48	71.9	38.6	D			Ia	A5	(K4)	19, 70
TT Lyr	2.09	0.03	tp	5.244	0.95	0.18	0.68	81.8	40.0	D			I	A	(K1)	19, 70, 74
UZ Lyr	1.12	0.03	p	1.892	0.96	0.28	1.00	79.0	25.0	D			Ia	A2	(G6)	37
β *Lyr*	0.81	0.43	t	12.92	0.63	0.26	0.42	74.0	8.0	D	0.77	0.75	II	B5	B8	5, 25

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a		Qual-ity	Sp_b	Sp_f	Reference
											D	U				
	m	*m*		*d*				°								
RU Mon	0.63	0.58	ap	3.584	0.58	0.13	1.19	87.6	1.1	D			Ia	A5	(A6)	6
RW Mon	1.72	0.17	t	1.906	0.79	0.22	0.74	90.0	6.5	D			II	A5	(G2)	70, 18
TU Mon	0.97	0.08	tp	5.049	0.94	0.22	0.85	80.1	22.0	D	0.98	0.97	Ia	B8	(G6)	25
UX Mon	1.74	0.14	t	5.905	0.80	0.21	0.59	90.0	11.0	D			Ia	A5	G7	79
UY Mon	0.75	0.75	p	5.340	0.50	0.39	1.00	85.0	1.0	D	0.87	0.86	II	—	—	G
AN Mon	1.10	0.10	t	2.446	0.64	0.16	0.59	83.6	5.5	U			II	—	—	G
AQ Mon	0.80	0.45	t	2.546	0.52	0.07	0.40	75.0	13.0	U			II	—	—	G
TV Mon	0.21	0.21	p	0.446	0.50	0.35	1.00	70.0	1.0	D	0.89	0.88	II	(G0)	(G0)	25
Z Nor	0.98	0.07	t	2.557	0.59	0.20	0.50	78.4	5.3	D	0.97	0.95	II	B5	(A5)	25
WZ Nor	1.20	0.60	t	1.049	0.67	0.30	0.90	90.0	2.2	U			II	—	—	G
GO Nor	2.20	0.20	t	5.957	0.86	0.30	1.00	90.0	6.0	U			II	—	—	G
GX Nor	1.00	1.00	t	0.269	0.50	0.40	1.00	90.0	1.0	U		0.80	Ia	(K0)	(K0)	G
U Oph	0.69	0.59	p	1.667	0.53	0.25	1.00	84.0	1.2	D	0.94	0.90	I	B5	B5	70, 37
RV Oph	2.03	0.11	t	3.687	0.82	0.13	0.62	85.9	12.2	U		0.98	I	A0	(G1)	9
RZ Oph	0.81	0.07	t	261.9	0.53	0.05	0.30	87.2	12.0	D			II	cG0	K5	70
SW Oph	1.22	0.03	t	2.446	0.90	0.21	0.60	74.8	24.7	D			Ia	A0	(K0)	73
SZ Oph	1.50	0.04	t	7.417	0.75	0.15	0.50	81.6	12.0	D			Ia	A	(G0)	25
UU Oph	2.48	0.03	t	4.397	0.90	0.19	0.70	85.3	18.0	D			Ia	A0	(G2)	25
WZ Oph	0.72	0.72	ap	4.183	0.51	0.08	0.98	89.4	1.01	U			I	G0	G0	G
Z Ori	0.87	0.07	ap	5.203	0.93	0.25	1.29	82.8	7.8	D			II	A0	(F7)	70
VV Ori	0.35	0.18	ap	1.485	0.86	0.49	1.92	80.2	1.7	U		0.96	Ia	B2	(B5)	84, 25
δ Ori	0.15	0.15	ap	5.733	0.75	0.38	1.61	62.6	1.1	U			IIIa	B1	(B2)	90
U Peg	0.60	0.40	p	0.375	0.60	0.45	1.00	75.6	1.5	U	0.93	0.88	Ia	F3	(F7)	25, 70
AQ Peg	2.75	0.02	t	5.549	0.92	0.15	0.62	85.6	30.7	D			Ia	A2	(K1)	25
AT Peg	0.78	0.23	p	1.146	0.82	0.32	1.00	77.6	4.6	D	0.88		Ia	A0	(F5)	43

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_b	k	i	γ	Sol.	b/a		Qual-ity	Sp_b	Sp_f	Reference
											D	U				
	m	*m*		*d*				°								
BX Peg	1.00	1.00	t	0.280	0.50	0.38	1.00	90.0	1.0	U		0.81	II	(K0)	(K0)	G
Z Per	2.43	0.02	t	3.056	0.89	0.15	0.63	90.0	21.0	D			I	A	(G2)	18, 70
RT Per	1.33	0.16	p	0.849	0.84	0.28	1.00	85.6	5.4	U		0.98	I	F2	(G5)	12, 70, 25
RV Per	2.41	—	tp	1.974	0.99	0.32	0.72	76.5	190.0	D			Ia	A	(K3)	19, 70
RW Per	2.20	—	t	13.20	0.87	0.08	0.47	90.0	30.0	D			IIa	A	(G1)	70
RY Per	2.03	0.10	t	6.864	0.85	0.18	0.72	90.0	10.0	0.3D			Ia	B6	F8	18
ST Per	2.15	—	t	2.648	0.87	0.13	0.45	80.0	33.0	D			Ia	A	(K0)	19
WY Per	2.70	—	t	3.327	0.92	0.15	0.61	84.1	29.7	D			Ia	F	(K4)	25, 69
AB Per	0.69	0.29	t	7.160	0.55	0.22	0.68	84.0	1.8	D	0.98	0.96	Ia	A4	(A9)	25, 44
AG Per	0.30	0.24	ap	2.029	0.72	0.26	1.43	78.3	1.3	U			Ia	B3	B3	35
β Per	1.13	0.04	tp	2.867	0.92	0.21	0.85	81.8	17.0	U		0.99	Ia	B8	(G4)	92, 70, 91, 5
X Pic	1.10	0.06	t	0.862	0.87	0.30	0.86	87.0	5.0	D			Ia	—	—	25
Y Psc	3.40	—	tp	3.766	0.97	0.18	0.77	85.7	67.0	D			II	A2	(K1)	70
V Pup	0.64	0.53	ap	1.454	(0.60)	0.46	1.10	74.0	1.2	D	0.89	0.81	Ia	B1	B3	70
RR Pup	1.10	—	tp	6.430	0.64	0.11	0.46	90.0	8.0	D			III	A?	(F7)	70
TY Pup	0.41	0.41	p	0.581	0.50	0.29	1.00	79.7	1.0	U	0.90	0.81	II	F0	(F0)	25
XY Pup	2.18	0.06	t	13.78	0.86	0.09	0.45	82.0	30.0	U			Ia	—	—	G
U Sge	2.88	—	t	3.381	0.93	0.22	0.78	90.0	21.0	D			I	B9	G2	18, 70
RS Sgr	0.74	0.21	ap	2.416	0.81	0.35	1.25	81.4	2.8	D			I	B5	(A4)	70
SX Sgr	0.93	0.11	t	2.077	0.76	0.21	0.65	83.7	7.4	D			Ia	A5	(F9)	25
WX Sgr	1.80	0.18	t	2.129	0.80	0.14	0.90	89.1	5.0	U			IIa	A0	(F2)	25
WY Sgr	1.10	0.20	t	4.670	0.64	0.11	0.60	85.8	5.0	U			IIa	B9	(F1)	25
XY Sgr	1.50	0.05	tp	2.023	0.95	0.24	0.90	89.0	27.0	D			Ia	A3	(K0)	25
XZ Sgr	2.80	0.08	t	3.276	0.92	0.10	0.50	85.5	46.0	U			IIa	A3	(K3)	25
YY Sgr	0.70	0.70	p	2.628	0.50	0.10	1.00	84.5	1.0	U			II	A0	(A0)	25

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_2	k	i	γ	Sol.	b/a D	b/a U	Quality	Sp_b	Sp_f	Reference
	m	*m*		*d*				°								
ZZ Sgr	1.08	0.02	tp	3.083	0.97	0.24	0.96	80.4	31.5	D			II	A2	(K1)	75
BN Sgr	0.85	0.40	tp	5.07	0.56	0.38	0.90	86.0	1.2	U			II	F5	(F7)	25
BQ Sgr	2.84	—	t	8.020	0.93	0.10	0.60	87.5	35.0	D			Ia	A2	(K2)	75
DV Sgr	1.16	0.09	t	1.863	0.66	0.20	0.65	83.9	5.2	D			Ia	A	(F1)	25
V356 Sgr	1.04	0.36	t	8.897	0.58	0.23	0.71	86.1	2.7	D			Ia	B9	A1	G
V431 Sgr	0.90	0.88	p	0.274	0.50	0.42	1.00	88.0	1.0	U			IIa	(K0)	(K0)	G
V497 Sgr	0.80	0.70	p	0.293	0.58	0.35	1.00	87.0	1.4	U			IIa	(K0)	(K3)	G
V505 Sgr	1.10	(0.04)	ap	1.183	0.95	0.32	1.04	82.0	11.0	U			Ia	A2	(G0)	86
FV Sco	0.70	0.08	a	5.728	0.80	0.22	1.28	87.0	2.5	D	0.98	0.96	II	B9	(F5)	G
RT Scl	0.77	0.36	tp	0.512	0.50	0.29	0.57	88.0	3.0	U		0.78	Ia	A5	(F7)	13, 70
U Sct	0.96	0.30	ap	0.955	0.90	0.42	1.47	83.0	4.2	D	0.90	0.85	II	G5	(K3)	70
W Sct	0.70	0.15	p	10.27	0.79	0.31	1.00	77.8	3.8	D	0.98	0.97	Ia	F?	(G5)	25
RS Sct	0.93	0.93	t	1.329**	0.50	0.27	1.00	90.0	1.0	D	0.91	0.85	IIIa	F	(F)	70
RY Sct	0.63	0.38	tp	11.12	0.60	0.34	1.00	77.0	1.5	U			III	Bq(5)	Bq(5)	G
RZ Sct	1.38	—	tp	15.19	0.90	0.16	0.50	76.2	36.0	D			III	B2	(G4)	70
VZ Sct	1.20	0.30	t	2.197	0.67	0.28	0.78	85.0	3.7	U			IIa	—	—	25
BN Sct	2.96	—	t	14.61	0.92	0.07	0.35	84.7	111.0	U			Ia	—	—	37
BS Sct	1.50	0.05	a	3.821	0.90	0.18	1.30	84.3	4.6	U			IIa	—	—	25
V Ser	0.94	0.24	tp	3.454	0.59	0.22	0.80	84.0	2.2	D	0.97	0.95	I	B8	(A5)	70
W Ser	1.10	?	t	14.15	0.60	0.35	0.90	—	—	—			IIIa	G1	G4	28
RS Ser	0.70	0.60	a	0.598	0.60	0.40	1.18	87.0	1.2	D			IIa	—	—	69
RW Tau	3.30	—	t	2.769	0.95	0.15	0.72	90.0	38.0	0.15D			I	A0	(G8)	18, 70
RZ Tau	0.60	0.60	t	0.344**	0.85	0.53	2.00	90.0	1.4	U			IIIa	F0	(F8)	65
SV Tau	1.09	0.15	p	2.167	0.77	0.29	0.82	80.8	4.9	U			I	A	—	46, 71a
λ *Tau*	0.35	0.05	p	3.953	0.85	0.27	1.00	73.0	5.8	U			IIa	B3	(K2)	70, 92

TABLE II, XXII—*Continued*

Star	A_1	A_2	Ecl.	Per.	L_b	r_2	k	i	γ	Sol.	b/a D	b/a U	Quality	Sp$_b$	Sp$_f$	Reference
	m	*m*		*d*				°								
RV Tel	1.71	(0.03)	t	8.328	0.79	0.13	0.58	84.6	11.2	D			Ia	A0	(F7)	25
V Tri	0.90	0.30	ap	0.585	0.87	0.34	1.11	87.5	5.0	D	0.93	0.88	Ia	A3	(F6)	25
X Tri	2.43	0.21	t	0.972	0.87	0.29	0.87	89.0	8.6	D	0.93		I	A3	(G5)	13, 80, 37, 38, 52
W UMa	0.60	0.60	p	0.334	0.50	0.37	1.00	76.0	1.0	D	0.85	0.75	Ia	F8	F8	70, 64, 95, 36
RW UMa	1.00	0.06	t	7.328	0.60	0.07	0.35	84.2	12.0	0.5D			I	F9	G9	18, 70
TX UMa	2.49	—	t	3.063	0.96	0.14	0.70	85.3	48.0	U			Ia	B9	A3‡	63
UX UMa	1.05	0.08	ap	0.197	0.91	0.23	1.11	83.5	7.8	D			I	A3††	(F9)	102
W UMi	1.11	0.15	a	1.701	0.91	0.43	1.37	83.3	5.9	D	0.96	0.94	I	A0	(F6)	8, 76, 16, 25
S Vel	1.39	—	t	5.934	0.72	0.12	0.52	90.0	9.6	D			Ia	A0	(F8)	70
RR Vel	0.91	0.15	tp	1.854	0.77	0.17	0.85	83.0	4.5	D			II	A	(F2)	70
AA Vel	0.20	0.20	tp	2.334	0.64	0.32	0.75	72.1	1.0	U			III	—	—	25
AL Vel	1.3	—	t	96.11	0.70	0.10	0.30	—	—	—			IIIa	A3p	—	G
UW Vir	3.96	0.02	t	1.811	0.97	0.19	0.73	86.0	70.0	U			I	A2	(K2)	81
AH Vir	0.46	0.46	tp	0.339	0.55	0.34	0.90	78.5	1.0	U	0.92	0.86	II	K0	(K0)	25
W Vol	0.90	0.09	tp	2.758	0.76	0.26	0.95	78.6	3.6	D			Ia	—	—	25
Z Vul	1.63	0.04	tp	2.455	0.79	0.21	0.56	78.9	12.0	D			I	B3	B3	21, 70, 25
RR Vul	1.32	—	t	5.050	0.70	0.10	0.48	86.0	10.5	D			Ia	A	(G0)	48
RS Vul	0.96	0.08	tp	4.478	0.80	0.20	0.76	79.0	7.0	U		0.98	Ia	B8	B9	7, 70, 40, 41, 25
BI Vul	0.80	0.80	p	0.252	0.50	0.38	1.00	89.0	1.0	U			II	(K0)	(K0)	G
AZ Vul	0.45	0.05	ap	1.123	0.93	0.41	1.45	74.1	6.8	U			II	—	—	22
B4520	*0.46*	*0.45*	ap	12.004	0.55	0.06	1.09	88.4	1.0	U		0.99	Ia	Oe	—	G
SZ Cam¶	0.27	0.22	tp	2.698	0.71	0.38	0.70	—	1.2	U		0.95	Ia	O9	—	Note

Footnotes to Table II, XXII

* $k = 0.85$, $i = 87^\circ.6^{54}$.

† $2c_b = 0.032$; $2c_f = 0.050$.

‡ $2_s = 0.05$.

§ The other values for *k* have been derived by Hopmann (Veöff. Leipzig, 6, 1936, k = 0.02; Krat (N.N.V.S., 5, 75, 1936), *k* = 0.034; and Gaposchkin (H.B. 900, 1935), *k* = 0.03.

** Period questionable.

‡‡ Largest deviation between observed secondary spectrum (A3) and computed one (K3).

†† Spectrum deduced from color index.

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The final table contains all the eclipsing binaries for which the light variation and orbital velocity of at least one component have been determined. All the data have been taken from Moore's "Fourth Catalogue of Spectroscopic Binaries,"[26] excepting those for VV Cephei,[27] TX Ursae Majoris,[28] and i Bootis.[29]

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TABLE II, XXIII

SPECTROSCOPIC ELEMENTS FOR ECLIPSING STARS

Star	K_b	K_f	γ	$a_b \sin i$	$a_f \sin i$	f_2	$m_b \sin^3 i$	$m_f \sin^3 i$	e
	km/sec	km/sec	km/sec	10^6km	10^6km	⊙	⊙	⊙	
AN And*	73.56	—	− 4.87	3.240	—	0.133	—	—	0.036
S Ant*	81.	148.	− 5.	0.722	1.320	—	0.52	0.29	0.
σ Aql*	163.52	199.	− 5.00	4.380	5.340	—	5.3	4.4	0.
TT Aur*	196.8	246.1	+10.2	3.600	4.500	—	6.7	5.3	0.0
WW Aur*	115.6	135.1	− 5.8	4.010	4.690	—	2.2	1.9	0.00
AR Aur*	107.2	116.0	+25.1	6.100	6.600	—	2.48	2.29	0.
β Aur*	108.96	111.04	−18.1	5.934	6.047	—	2.21	2.17	0.00
ε Aur*	15.7	—	− 2.5	2014.	—	3.34	—	—	0.33
ζ Aur*	23.78	12.65	+10.73	294.3	553.4	—	16.0	8.5	0.411
i Boo*	350.		—	1.4		—	1.2		0.0
RS CVn*	91.6	99.0	− 8.9	6.040	6.530	—	1.79	1.66	0.0
R CMa*	28.64	—	−39.70	0.443	—	0.003	—	—	0.138
UW CMa*	217.1	287.6	−10.6	12.956	17.163	—	32.2	24.3	0.156
RZ Cas*	69.30	—	−38.32	1.137	—	0.041	—	—	0.052
TV Cas*	87.92	150.	+ 0.54	2.191	3.739	—	1.60	0.94	0.0
UU Cas	161.	—	−56.	18.863	—	3.693	—	—	0.
YZ Cas*	71.46	—	+ 9.97	4.390	—	0.169	—	—	0.0
AO Cas*	218.45	234.59	−29.34	10.578	11.360	—	17.60	16.40	0.037
AR Cas	59.06	—	−14.78	4.920	—	0.120	—	—	0.224
CC Cas	141.65	291.79	− 4.19	6.528	13.447	—	18.88	9.17	0.102
U Cep*†	109.7	—	− 6.0	3.320	—	0.235	—	—	0.474
VV Cep*‡	20.5	—	−20.6	2030.	—	6.05	—	—	0.25
AH Cep*	225.3	261.2	−20.6	5.495	6.371	—	11.4	9.8	0.034
U CrB*	80.1	211.7	− 7.65	3.79	10.02	—	6.44	2.43	0.072
RW CrB*	61.	—	−11.	0.600	—	0.017	—	—	0.12

TABLE II, XXIII—*Continued*

Star	K_b	K_f	γ	$a_b \sin i$	$a_f \sin i$	f_2	$m_b \sin^3 i$	$m_f \sin^3 i$	e
	km/sec	km/sec	km/sec	10^6km	10^6km	⊙	⊙	⊙	
α CrB*	34.83	—	+ 2.61	7.701	—	0.060	—	—	0.377
Y Cyg*	244.8	241.3	—51.8	9.96	9.86	—	17.2	17.4	0.136
GO Cyg*	133.2	156.2	+ 3.2	1.315	1.542	—	0.98	0.83	0.0
MR Cyg*	147.0	172.9	—26.0	3.364	3.957	—	3.51	2.56	0.122
TW Dra*	65.78	—	— 0.34	2.535	—	0.083	—	—	0.054
YY Gem*	114.0	126.7	+ 4.3	1.276	1.419	—	0.63	0.57	0.0
Z Her*	88.2	101.8	—46.5	4.800	5.600	—	1.5	1.3	0.00
RX Her*	130.6	146.5	—24.9	3.194	3.583	—	2.08	1.85	0.00
TX Her*	121.0	140.2	— 6.4	3.427	3.971	—	2.05	1.76	0.0
AK Her*	78.	—	—13.	0.452	—	0.021	—	—	0.0
u Her*	99.50	253.	—21.16	2.800	7.120	—	6.8	2.6	0.053
RT Lac*	62.5	116.0	—47.0	4.360	8.090	—	1.9	1.0	0.
AR Lac*	120.02	119.19	—36.25	3.270	3.247	—	1.4	1.4	0.041
CM Lac*	117.5	159.	—17.5	2.593	3.509	—	2.0	1.5	0.
δ Lib*	75.60	—	—35.38	2.419	—	0.105	—	—	0.012
RR Lyn*	67.19	—	—13.74	9.127	—	0.310	—	—	0.081
β Lyr*	183.71	—	—19.02	32.600	—	8.33	—	—	0.014
U Oph*	179.9	204.6	—11.5	4.147	4.718	—	5.27	4.63	0.00
WZ Oph*§	92.5	—	—16.8	5.29	—	0.326	—	—	0.10
VV Ori*	132.37	—	+20.77	2.704	—	0.358	—	—	0.00
δ Ori	101.53	—	+21.25	7.958	—	0.613	—	—	0.106
η Ori	144.8	—	var.	15.900	—	2.51	—	—	0.016
AG Per	164.97	187.32	+15.84	4.349	5.165	—	4.86	4.29	0.051
β Per*	43.96	—	+16.30	1.732	—	0.025	—	—	0.033
V Pup*	604.0		—	12.5		—	37.0		0.08

TABLE II, XXIII—*Continued*

Star	K_b	K_f	γ	$a_b \sin i$	$a_f \sin i$	f_2	$m_b \sin^3 i$	$m_f \sin^3 i$	e
	km/sec	km/sec	km/sec	10^6km	10^6km	⊙	⊙	⊙	
μ¹ Sco*	480.0		—	9.5		—	16.5		0.05
U Sge*	67.9	224.0	—15.1	3.155	10.411	—	6.70	2.03	0.035
μ Sgr††	66.82	—	— 8.23	148.11	—	4.0	—	—	0.447
λ Tau*	55.95	—	var.	3.037	—	0.072	—	—	0.055
W UMa*	134.	188.	— 5.	0.610	0.860	—	0.67	0.48	0.00
TX UMa*	54.2	181.	—12.	2.25	7.47	—	3.0	0.9	0.188
W UMi*	105.5	—	— 7.7	2.470	—	0.21	—	—	0.0
α Vir	126.8	202.	+ 0.5	6.965	11.096	—	8.97	5.63	0.10
AG Vir	80.	—	—16.	0.700	—	0.034	—	—	0.10
Z Vul*	96.58	213.74	—15.11	3.252	7.215	—	5.24	2.36	0.0
RS Vul*	54.98	175.9	—22.04	3.388	10.842	—	4.34	1.35	0.053
B4520*	192.4	—	—41.8	31.700	—	8.84	—	—	0.065

* Photometric elements have been derived.

† Elements must be regarded as very provisional.

‡ Second component definitely present; approximate mass ratio is 1: 0.8.

§ Second component definitely present; most probable mass ratio is 1:1.

†† Shown photoelectrically to be variable with a range of $0^m.14$ (Morgan and Elvey, Ap. J., 88, 110, 1938).

25. Some Important Eclipsing Systems.—Among the two hundred and seventy eclipsing binaries studied in regard to their dimensions and physical properties, there are several that occupy special places in our knowledge. Some of them present incompletely solved problems. They are now briefly described, arranged by constellations.

AR Aurigae.—Established in 1934, this system may be of importance for the determination of the accurate temperature of an A star. The star is near enough to permit a direct determination of parallax. The minima are both deeper than $0^m.5$; there is no sign of ellipticity, so that relative sizes can be very accurately determined; the orbital velocities of both components (A0 + A0) have been observed, and absolute dimensions could therefore be determined with high precision.

β *Aurigae.*—Discovered to be a spectroscopic binary in 1889 (Pickering), this star has two shallow minima, $< 0^m.10$ (Stebbins), so that there must always be some uncertainty in the relative elements. Hitherto the values $k = 1.00$ and $\gamma = 1.00$ have been adopted, in harmony with the spectroscopic elements. Of the second apparent magnitude, this system of two A0 stars has a reliable trigonometric parallax, and from this point of view β Aurigae has been considered the best A0 star for establishing a temperature for the class. The relative elements, however, are not too well established, a point that should be kept in mind in theoretical applications.

ε *Aurigae.*—This system, discovered in 1821 and shown to be an eclipsing star in 1902 (Ludendorff), surpasses every other eclipsing variable in length of period (27.08 years). It is approached only by V381 and V383 Scorpii, discovered in 1936, with periods of 18 and 13.4 years respectively, and by VV Cephei, with a period of 20 years, also discovered in 1936 (see below).

The duration of eclipse for ε Aurigae is about two years, of which totality occupies somewhat less than a year. From these exceptional values the densities of the components are computed to be of the order of 10^{-6} ⊙ and 10^{-9} ⊙, respectively, comparable only with the densities of the stars just mentioned, and a few other red super-giants.

The most remarkable fact concerning ε Aurigae is that *though only one spectrum is observed outside the eclipse, the spectrum during eclipse remains almost unchanged*; moreover, there is no appreciable change in (blue-yellow) color index during the minimum. There is some evidence of asymmetry for a few of the lines (notably 4444 and 4468) during the eclipse, though the detailed correlation with the eclipse phenomenon is not very clear. Several hypotheses have been suggested to explain the anomalies, the most recent being that of Kuiper, Struve, and Strömgren[26], who ascribe the eclipse to the atmosphere, rather than the body, of the fainter component. There is no escape from the conclusion that, under our conventional assumption that stars are spherical or nearly so, the fainter component of ε Aurigae is one of the largest stars in the sky. Indeed, there is only one definitely known eclipsing system (VV Cephei) of which the red supergiant component is practically of the same size; very probably the fainter component of V381 Scorpii is another.

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[26] Kuiper, Struve, and Strömgren, Ap.J., 86, 575, 1937.

Since observationally we have no indication of the physical properties of the second component, except its relative size, there is a wide range of possible solutions for its absolute dimensions. Limiting values for the dimensions of this gigantic system, from the elements given in the main table, are summarized below:

r_b	167 $\odot$	to 238 $\odot$	T_e, brighter	6300°	to 3300°
r_f	1670$\odot$	to 2380$\odot$	T_e, fainter	970°	to 1480°
m_b	12.0	to 43.7	M_{bol}, brighter	−3.1	to −7.3
m_f	12.0	to 26.2	M_{bol}, fainter	−2.0	to −6.5

The next eclipse (primary) will begin in 1955.

ζ *Aurigae.*—Established as an eclipsing binary by Guthnick in 1932, this system presents a wonderful study of two components that differ greatly in spectral class, surpassed in this respect only by VV Cephei. It has a conveniently short period (less than three years); the orbital velocities of both components are observed, and thus the absolute dimensions can be considered well determined, although there is still some uncertainty in the ratio of the radii.

The most striking feature is the existence of an extensive atmosphere around the K5 supergiant. As the blue component is much smaller than the red, the light of the blue star can be carefully studied as it passes through the atmosphere of the K5 star at the beginning and end of eclipse. A small secondary fluctuation of light is shown by ζ Aurigae both between and during eclipses; it is undoubtedly connected with the red supergiant. Similar secondary fluctuations are found for ε Aurigae and for VV Cephei; for both systems the fluctuations persist through the minima.

i Bootis—Established as an eclipsing variable in 1926 (Schilt), this system, of spectral class G2, is important on account of its large and well-determined trigonometric parallax ($0''.076$), and as constituting one component of the visual double star Σ 1909 = Boss 3846. Photometric observations are only possible at times of greatest separation, and when (as at present) the components are very close together, only the variations of the combined light are observable; hence the observed range falls from its true value of half a magnitude to about two-tenths.[27] There are very few spectroscopic observations, so that the absolute dimensions given in the preceding tables must be considered provisional.

AO Cassiopeiae.—Established as variable by Guthnick in 1921, and as an eclipsing system by Pearce in 1928, this star is an example of a very massive eclipsing variable, surpassed in our present knowledge only by UW Canis Majoris and by VV Cephei. The velocity curve is well established, but the minima have depths of less than $0^m.2$, so that the relative elements (and consequently the absolute dimensions) are only approximate.

UW Canis Majoris.—This system, shown by Gaposchkin in 1936 to be an eclipsing star, is the twin of AO Cassiopeiae in masses, spectra, sizes, and densities. The light curve shows two minima, rather deeper than those of AO Cassiopeiae (photographically $> 0^m.3$); if these depths can be photoelectrically confirmed, the system of UW Canis Majoris will provide better material than AO Cassiopeiae for a determination of absolute dimensions.

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[27] Shapley and Calder, H.B. 907, 1938.

U Cephei.—The classical case for the study of limb darkening is provided by U Cephei (discovered in 1880 by Ceraski); the difference in size and type of eclipse are fortunate for this problem. It also presents a favorable opportunity for the study of change of period, for the decrease of brightness is rapid, and a definite phase is therefore accurately determinate.

VV Cephei.—This system, shown to be an eclipsing variable in 1936-37 (McLaughlin, Gaposchkin) combines the properties of the gigantic system of ε Aurigae with a clean-cut case of high disparity between components, as in ζ Aurigae. The orbital velocity of the blue component is not well observed, so that the absolute dimensions given in the catalogue are not definitive, although they cannot be far from the true values.

The spectrum shows some remarkable properties: the bright hydrogen lines disappeared during the eclipses of 1895 and 1936, but the bright lines of FeII, [FeII], and [SII] did not disappear. There is moreover a fluctuation, probably originating in the red component, that has an amplitude of at least $0^m.35$. There is also spectroscopic evidence for a large atmosphere surrounding the red component, as with ζ Aurigae. None of these peculiarities has as yet been completely interpreted. The next eclipse will begin in 1956, soon after that of ε Aurigae.

W Crucis.—Discovered as an eclipsing variable by Miss Leavitt (1904), this star is important because, in spite of its long period (198^d), the components show marked ellipticity. Unfortunately there are no known determinations of the orbital velocities of the components, so that the absolute dimensions are not certain. The light curve, however, is well established, and therefore the relative dimensions for this supergiant G system are rather well determined.

Y Cygni.—Discovered to be an eclipsing star by Chandler in 1886, this system is a splendid subject for theoretical investigations in the realm of massive, hot stars, for both minima are deep, no ellipticity of the components is observed, and orbital velocities for both stars are well determined. The absolute dimensions may be regarded as accurate to within five per cent. The system is, besides, a good example for the study of apsidal motion.

YY Geminorum.—The system of Castor C, established as an eclipsing system in 1926 (van Gent, Adams and Joy), has the latest dwarf spectrum (M1) observed both spectroscopically and photometrically. It is one of the best determined eclipsing systems in both these respects. It has the large parallax of $0''.076$, so that it may serve as the cornerstone for the temperature scale of M dwarfs. The spectroscopic peculiarities are described on page —.

β Lyrae.—Known to be an eclipsing variable since 1784 (Goodricke), this system probably presents the most wonderful known example of spectroscopic peculiarities. From the light curve it seems clear that we are dealing with two ellipsoidal bodies, not very different in size or brightness. Spectroscopically there is evidence for one massive component, which revolves in the same period as that of the light variation. The mass function computed from this component is more than $8\odot$—one of the largest values ever definitely determined for a spectroscopic binary. Besides the spectrum of Class B8, there is another spectrum, originally described as of Class B5

(Curtiss, Baxandall), concerning whose velocity curve there is not as yet any unanimity of opinion; alternative views relate it to a very massive star, and to an atmosphere investing both components, the second of which gives no observable spectrum. The so-called B5 spectrum is not typical for the class. Besides these two absorption spectra, the system shows a number of bright lines, which vary both with the period and independently of it. Further, there is another system of absorption lines flanking the bright lines, and showing velocities independent of the B8 and B5 spectra. No complete interpretation of the peculiarities has ever been achieved. The accompanying table gives a condensed description of the variations during the light cycle, counted from principal minimum. The following abbreviations are used: B8 = spectrum of B8 component; B5 = spectrum of B5 component; Br = bright lines; R = red side; V = violet side; W = wing.

Phase	Description
0^d to 1^d	B8 and B5 not sharp, but strong; Br have maximum on R of B5 lines; W visible.
1 to 2	B8 strong; B5 weak, begin to be separable; Br still maximum on R, but also visible on V; W very weak.
2 to 3	B8 well defined; B5 covered by Br, which are still to R of B8 + B5; W weak, seen to V and R of B8 on HeI 4471, 4026.
3 to 4	B8 shows maximum displacement to V; B5 measured at Hβ, 4471, 4026, 3964. Br not visible beyond V of B8; still strong to R; W not easy to measure.
4 to 5	B8 still strong; B5 uncertain, except at Hβ; Br still not visible beyond V of B8; W to R becoming measurable.
5 to 6	B8 + B5 blend; single lines sharp; B5 faint; Br becomes visible on V of B8; W are distinct.
6 to 7	B8 + B5 begin to separate with equal strength; Br on both sides of B8, B5 (at 4471 and Hβ); W seen in details.
7 to 8	B8 + B5 well separated; Br on both sides of Hβ, 4471, but for Hγ, entirely on V. Other Br seen on V of B5. W seen in details on R.
8 to 9	B8 + B5 well separated, though hazy. Br remain strong on V of B5, but begin to appear on R, very weak. W weak?
9 to 10	B8 at maximum of displacement to R; Br do not extend beyond R of B8, and are symmetrical to B5, with maximum to R; W stronger.
10 to 11	B8 + B5 not much changed; Br still stronger to R, though V becomes strengthened; W strengthening.
11 to 12	B5 and B8 close together; Br either stronger or equal in strength on violet; an absorption component appears at a displacement of +200 km/sec.
12 to 12.9	B8 + B5 are difficult to resolve; component at +200 km/sec persists; Br stronger to R.

A redetermination of the elements is in progress at Harvard.

WZ Ophiuchi.—Discovered as an eclipsing system in 1923 (Leiner) and rediscussed in 1936-37 (Sanford, Gaposchkin), this system occupies an important place among eclipsing stars, for both components are similar to the sun, being non-elliptical, with spectra of Class G0. Photometrically the system is well determined, with two minima deeper than $0^m.7$.

δ *Orionis.*—Possibly this system is triple; in other respects its properties are at present little known.

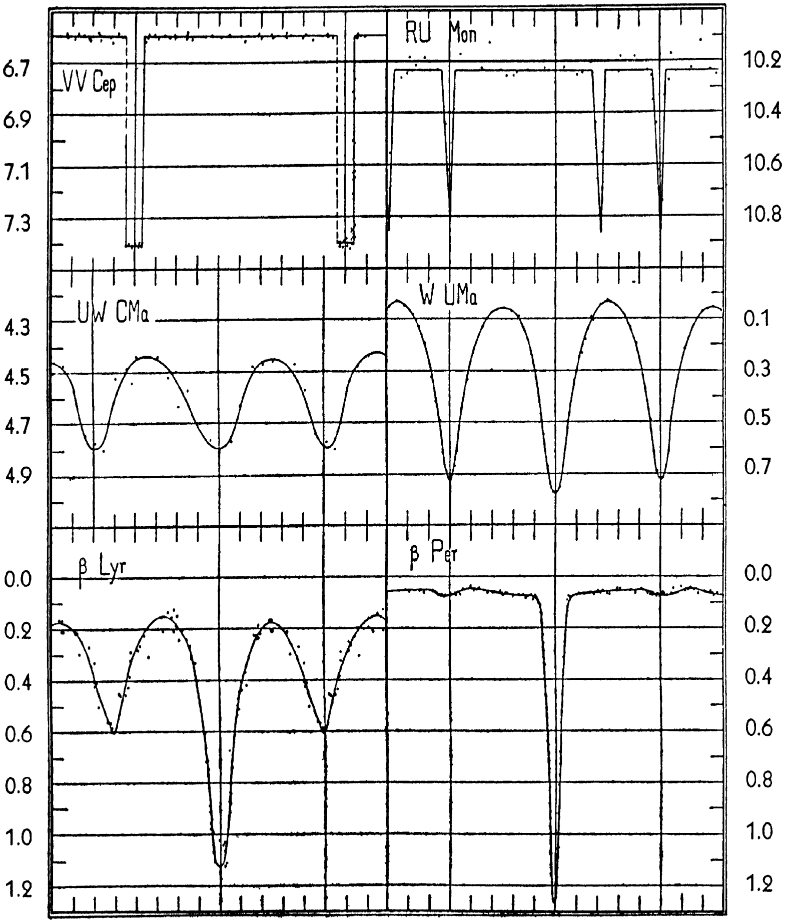

Figure II, 1.—Light curves for six eclipsing stars. Abscissae are phases (short vertical lines indicate intervals of one tenth of the period). Ordinates are magnitudes, as indicated in the margins. Sources of data are as follows:—VV Cephei, S. Gaposchkin (H.C. 421, 1938, and unpublished); the minima shown are those of 1915-1916 and 1936-1937. RU Monocerotis (visual observations), Dubiago, A.N., 235, 235, 1928. UW Canis Majoris (photographic observations), S. Gaposchkin, H.B. 902, 1936. W Ursae Majoris (photoelectric observations, relative magnitudes), C. M. Huffer, Ap.J., **79**, 375, 1934. β Lyrae (photoelectric observations, relative magnitudes), Smart, M.N., **95**, 648, 1935. β Persei (photoelectric observations, relative magnitudes), Smart, M.N., **97**, 403, 1937.

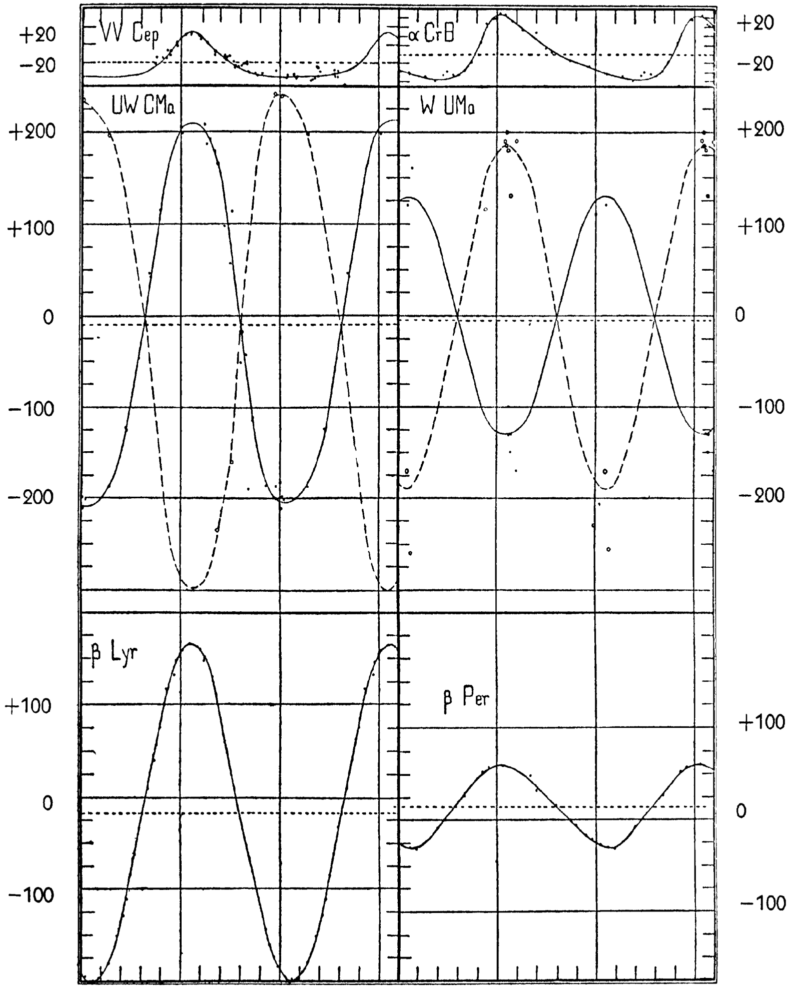

Figure II, 2.—Velocity curves for six eclipsing stars. Abscissae are as in Figure II, 1, for the five stars common to the two figures; short vertical lines indicate intervals of one tenth of the period. Ordinates are kilometers per second, as indicated in the margins. Sources of data are as follows: VV Cephei, S. Gaposchkin, H.C. 421, 1938 (single observations). α Coronae Borealis, Jordan, Publ.Allegh.Obs., **1**, 91, 1909. UW Canis Majoris, Pearce, Publ.Dom.Ap.Obs., **6**, 51, 1932; Luyten and Ebbighausen, Ap.J., **82**, 247, 1935. W Ursae Majoris, Adams and Joy, Mt.W.Contr., **8**, 358, 1919. β Lyrae, Rossiter, Publ.Mich.Obs., **5**, 88, 1933. β Persei, McLaughlin, Publ. Mich.Obs., **6**, 3, 1934.

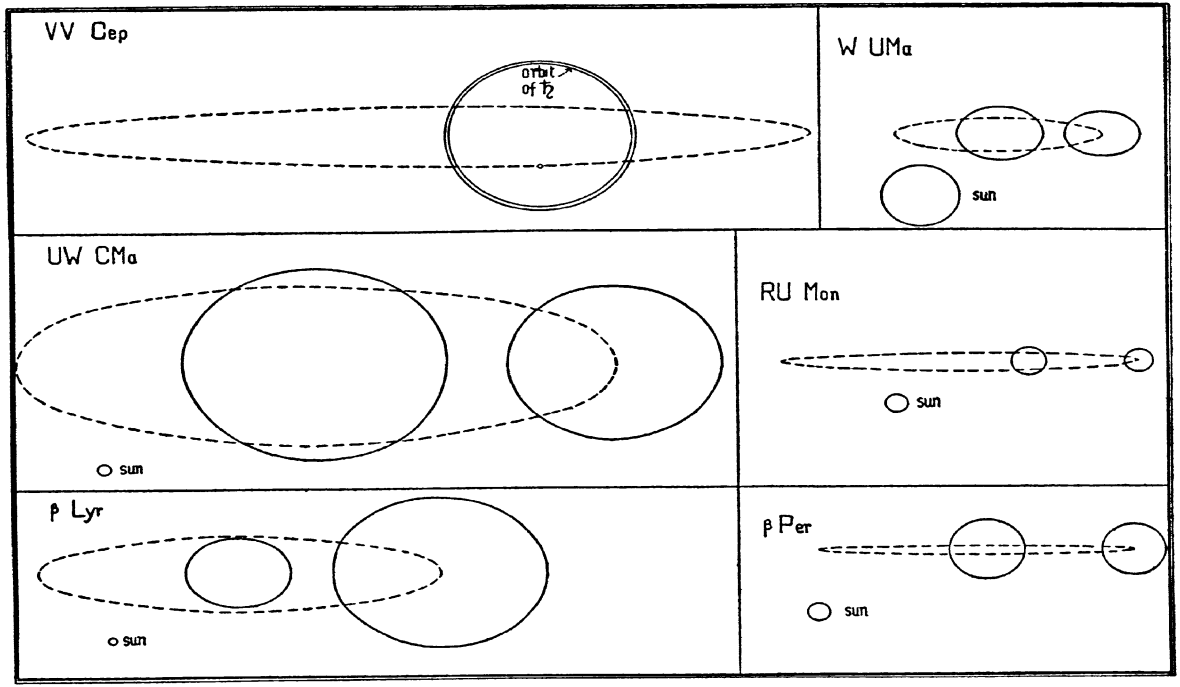

Figure II, 3.—Six eclipsing systems. The scale for the sizes of the components is indicated for each system by comparison with the sun, except for VV Cephei, where the orbit of Saturn is used for comparison (circle just inside the larger component). The orbits are shown as projected on the plane of the sky.

β Persei.—Algol, discovered in 1669 by Montanari, offers at present one of the best examples of rotation effect. Two determinations of the effect, however, having led to results that differ by 100 per cent, we must conclude either that the measurements are not yet reliable, or that the system of Algol is an ill case for the study of the problem. At the present time our definite knowledge of the system of Algol has not advanced greatly over its state twenty years ago.

RY Scuti.—This star was shown to be an eclipsing system in 1936 by Gaposchkin. Its spectrum is unique, showing principally the bright lines at 4658 (CIV?), 4701([A IV]?), 4734([A IV]?), 4755, and 4770, which are associated with bright lines of hydrogen and helium, as in the spectra of a few nebulae and of R Aquarii. As there are almost no absorption lines in the spectrum, its spectral classification is difficult; it may be described as a bright line spectrum of high excitation. Through a private communication we learn from Merrill that RY Scuti shows in emission the yellow and red lines of [N II]. In length of period, shape of light curve, and possibly in spectral peculiarities, RY Scuti resembles β Lyrae. Probably they are also similar in dimensions and physical properties. A determination of the velocity curve is much to be desired.

W Serpentis.—The nature of the light curve of this peculiar star was established independently in 1936-37 by Gaposchkin and by O'Connell. The light curve is unique: instead of a secondary minimum it shows an increase of brightness, flanked on each side by secondary minima of somewhat differing depths; this unusual form of light curve persists, surprisingly, over the whole observed interval of 35 years. At the principal minimum there are forbidden bright lines of ionized iron (as in the spectra of some long-period variables at minimum, of four "slow" novae, and of VV Cephei). The absorption spectrum varies from cG1 to cG4. We have included W Serpentis among eclipsing stars on rather arbitrary grounds; a combination of spectroscopic and photometric observations is necessary to determine whether the object is a double system, an intrinsic variable, or both.

V 381 Scorpii.—Discovered in 1936 as an eclipsing variable (Miss Swope), this system seems to be a rival of ε Aurigae in respect to its spectrum and period. The period is about 18 years (=6475 days), and the duration of eclipse, about $0^P.13$. The range is one of the largest among eclipsing stars—about $3^m.7$ photographically. The eclipse lasts 670 days, and totality, about 300 days. The spectrum is of Class F5. If we use these values, we obtain the following results: $L_b = 0.97$; $k = 0.50$; $i = 90°$; $r_b = 0.21\ A$; $r_f = 0.42\ A$; $Sp_b =$ F5 ($T_e = 6300°$); $\alpha = 0.25$; $m_b = 101\ \odot$; $m_f = 25.2\ \odot$; T_e, fainter, $= 1440°$; $R_b = 1500\ \odot$; $R_f = 3000\ \odot$. All these values, especially the spectrum of the brighter component and the physical character of the fainter, indicate a system similar to that of ε Aurigae. We should point out that the size and mass given above for the brighter component are maximal values, thus the size derived for the fainter star is a minimum.

If we compute the absolute bolometric magnitude of the brighter component in accordance with the relation $L \propto m^{3.2}$, we obtain a value of -10. There is very little likelihood that the ratio of the radii (0.5) has been underestimated. If the above absolute bolometric magnitude is regarded as improbably high, the only solution is that the adopted temperature of 6300° is too high. Here again, as in many other cases, the existence of a lower temperature seems probable.

UX Ursae Majoris.—This system, discovered in 1933 by Beliavsky, has the shortest period ($0^d.197$) known among eclipsing stars, a fact that leads inevitably to a density of the order of $20\odot$. A recent investigation[28] leads to a color index of $+0^m.13$, indicating a spectrum near to A3. We find that UX Ursae Majoris belongs to a small group of stars that occupies a position between the white dwarfs and the main sequence in the Russell-Hertzsprung diagram, a conclusion reached also by Kukarkin and Zverev. The trouble of determining the spectral class directly would be well repaid.

C. P. D. —66°3307.—Discovered in 1936 by Mrs. Mayall[29], this is one of the most peculiar of variables. Outstanding are its long period (605 days), and its spectrum of P Cygni type, with bright lines flanked by strong absorption on the violet side. Though the scattering of observations is considerable (evidently owing to intrinsic variation of at least one component) there is no doubt that —66°3307 is an eclipsing star with a range of over two magnitudes, and a duration of eclipse of about $0^P.15$. As the light curve is too uncertain for a determination of k and r_b, we shall adopt average values. If we adopt a temperature of 23,000° for the brighter component, we obtain a mass of about $600\odot$ for the whole system—the largest mass we have obtained for any eclipsing system. If we conclude that this high mass is improbable, we may reconcile a more "probable" mass with a temperature of about 1500°. Perhaps we can reconcile the two pictures by assuming that the P Cygni star consists of a high-temperature nucleus, and a large envelope at a much lower temperature.

B. D. +6°1309.—It is very probable that this most massive spectroscopic binary ("Plaskett's star") is an eclipsing variable with a range of about $0^m.10$. If we adopt a temperature of 25,000° for this system in accordance with its spectrum (O9) and assume the maximum value for the relative dimensions, the mass computed by our method is only about $100\odot$, whereas the observed minimum mass, based on the spectroscopic elements, is over $200\odot$. This discordance cannot be easily resolved, unless we adopt a much higher value for the temperature of an O9 star; thus the mass must still be considered uncertain. The difference between observed and computed mass has its largest negative value for this star; most of the other O stars show positive differences.

[28] Kukarkin and Zverev, N. N. V. S., 5, 125, 1937.

[29] M. W. Mayall, H. A., 105, No. 25, 1936.

C

INTRINSIC VARIABLES

CHAPTER III

THE GREAT SEQUENCE, I
LONG-PERIOD VARIABLES

> Age cannot wither her, nor custom stale
> Her infinite variety
>
> Shakespeare

The stars assigned to the Great Sequence form a related series, with periods ranging from less than a hundred minutes to more than two years. They are continuously variable in brightness, intensity distribution (color), spectrum, and radial velocity.

The Great Sequence stars of longest period are the latest in spectral class, and the largest in size, since they all belong in that rare category, the giant or supergiant branch of the Russell diagram. There is an increase in absolute (visual) brightness from the shortest to moderate periods; but the absolute visual magnitudes of the stars in the long-period group are smaller than those of ("classical") Cepheids of rather shorter period, and more comparable with those of the cluster-type stars.

The writers have treated the members of the Great Sequence as far as possible as a united group, though for convenience of reference they are distributed in several chapters. A study of the shapes of their light curves, based on numerical parameters that are described later in the present chapter, has recently been published by one of the writers[1]. In the paper just cited it is shown that the stars of the Great Sequence fall into several groups, separated by minima of period-frequency, which occur approximately at eighty days, at nine days, a day and a half, and perhaps two-tenths of a day. Within each of the corresponding five groups of stars there is a progression, with period, of the form of the light curve, which becomes more asymmetrical the longer the period. For stars of the two short-period groups the space-velocity is high; for stars of the next two groups it is much lower, and possibly decreases somewhat between them; for stars of the long-period group the space velocity is again high. The average spectrum appears to progress uniformly with period for stars of period greater than one day. It is, however, not impossible that the progression of spectrum with period is small *within each group*; within the two groups of shortest period, especially the group containing the "cluster-type stars", it is known to be insensible. The uniformity of the period-spectrum relation may possibly be the result of a partial overlapping of the groups in period; indeed there are suggestions, both in the data for radial velocities and in the frequency of period as a function of galactic longitude, that the long-period group actually consists of two overlapping groups, with maximum period-frequency at about 220 days and 350 days, respectively.

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[1] S. Gaposchkin, P.N.A.S., 24, 1, 1938.

The little-known group containing the "Beta Canis Majoris" stars may be regarded as belonging to the dwarf Cepheids—main sequence stars that are varying in a Cepheid-like manner. Their probable densities are compatible with a period-density relation like that shown by the stars of the Great Sequence. They do not, of course, conform to the period-spectrum relation that is shown by the stars of the Great Sequence; but the period-spectrum relation, though conspicuous, is not a fundamental law. Most of the Beta Canis Majoris stars are still very inadequately observed, and their properties uncertain.

A large number of stars of somewhat indefinite properties show a behavior that resembles that of Great Sequence stars closely enough to justify classifying them as related to the more regular members. They are continuously variable in brightness, color, spectrum, and (probably) radial velocity, but they differ from the normal members of the sequence in having variable mean magnitudes, amplitudes, or shapes of light curves (sometimes two of these characteristics, sometimes all three); all, however, show periodicity. They have usually been characterized as semi-regular. They appear to conform, roughly at least, to the period-spectrum relation. Most of them fall in the interval of minimum period-frequency near to eighty days, and capricious behavior is seemingly typical for stars that have infrequent periods. All the peculiarities shown by these relatives of the Great Sequence stars may be found to a smaller degree in normal members of the Sequence.

26. Long-Period Variables. *Definitions*—The long-period variables, often called "Mira Stars" after their prototype, o Ceti, are somewhat difficult to define precisely, because there has hitherto been no complete interpretation either of their light curves or of their radial velocities. Ludendorff[2] adopts, as a definition of the class, two main criteria: (i) the light variation is periodic, with periods between 90 and 600 days; (ii) the star is a red star with a visual amplitude of at least one and a half magnitudes. This definition, of course, includes only stars whose light curves cannot be interpreted in terms of an eclipse. There are, however, several undoubted long-period variables that do not fulfill Ludendorff's two definitions; RU Velorum, for example[3], has a period of 63 days, with a spectrum of Class M3e. At the other extreme, VX Sagittarii has a period of 731 days. The restriction on the amplitude is probably imposed by observational selection, stars of small amplitude and long period being difficult to establish: we may select as examples WY Andromedae ($P=109$ days, amplitude $1^m.3$), Y Serpentis ($P=385$ days, amplitude $1^m.1$), and TV Aurigae ($P=372$ days, amplitude $0^m.8$). The limits imposed by Ludendorff's criteria would need to be extended both in regard to period and to amplitude.

More elastic definitions are made by Townley, Cannon, and Campbell[4]: "1. A variation in a period of fifty days or more, provided the star has not been assigned definitely to another class of variables. 2. A range of variation of at least two and a half magnitudes. . . . 4. A spectrum of Class Me or Se, generally indicative of long-period variables".

[2] Ludendorff, Handbuch der Astrophysik, 6, 89, 1928; *see* de Kock, Utrecht Publ., No. 10, 1933.

[3] Payne, H. B. 861, 1928.

[4] H. A., 79, Part 3, 1928.

The R Coronae Borealis and U Geminorum variables (SS Cygni stars), included in the catalogue just mentioned, are assigned by us to the irregular and cataclysmic variables respectively, and the RV Tauri stars are discussed in Chapter VI; although closely related to the long-period variables they can probably not be usefully included in the class. The first definition of the Harvard Catalogue of Long-Period Variables, just quoted, includes all probable members of the group; the second involves the same criticism as Ludendorff's second criterion; the last does not exclude the dwarf eclipsing star YY Geminorum (dM1), the irregular variable T Microscopii[5] (M6e) or AG Aurigae[6] (cG5e) and SX Herculis (gG7ev). Nor does it cover the numerous long-period variables with spectra of Classes N, R, and S. However, all the criteria *taken together* will define a long-period variable with considerable success.

For the purposes of the present investigation we adopt the following elastic definition: A long-period variable is a periodic star that has a period of more than 40 days, that is neither an eclipsing star nor a Cepheid variable, and that has a variable spectrum of late type (G or later) showing giant characteristics, and often, though not always, bright lines. The distinction between long-period variables and Cepheids is a difficult one to draw in special cases, for the two groups undoubtedly overlap, both in period and in spectrum: long-period variables with periods less than 100 days are AG Aurigae ($98^d.3$), T Centauri, ($90^d.7$) and RU Velorum (63^d); and there are several Cepheids known with periods greater than fifty days, such as the two stars in the Small Magellanic Cloud with periods of 66 days and 127 days, one star[7] in N. G. C. 6822 with a period of about 150 days, and the galactic star CG Sagittarii (64^d). The overlap in spectrum is less striking, for long-period variables with spectra of Classes G or K are uncommon: we have, however, AG Aurigae and SX Herculis, quoted above, among the long-period variables, and KQ Scorpii (K2) and TX Cygni (K2-K7) among the Cepheids; there are even a few Cepheids known that reach

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[5] Unpublished Harvard observations.

[6] Harvard photographic observations, unpublished.

[7] Hubble, Ap. J., 62, 409, 1925.

Class M (Z Scuti, G0–M0; RU Scuti, G5–M; SV Vulpeculae, G2–M0), though there are none of Classes S or N, and (excepting RU Camelopardalis and VX Cygni) none of Class R. Despite the overlap in period and spectrum, the long-period variables and Cepheids must be regarded as two related groups, rather than a continuous series.

27. Lists of Long Period Variables.—In the article on variable stars in The Handbuch der Astrophysik[8], Ludendorff gives a list of well-observed long-period variables, and descriptions of their light curves. This list was superseded four years later by another[9]. Ludendorff's two lists contain only the brighter stars of known light curve and spectrum; a far completer list, containing all stars suspected in 1928 to be long-period variables, is the Harvard Catalogue of Long-Period Variables[10], which forms the basis of the lists given in the present chapter.

In Prager's "Katalog und Ephemeriden" for 1936, there are 2027 long-period variables with periods determined or estimated. Details concerning the majority of these stars, which are faint, and known from limited series of photographic observations, must be sought in the literature, and may be found by means of the "Geschichte und Literatur". But there are between four and five hundred long-period variables that are brighter than the tenth magnitude at maximum, and for most of these we have not only spectroscopic information, but also extensive and often continuous series of photometric data. By far the greater part of our information concerning the changes of brightness of this well-observed group of long-period variables has been contributed by amateur astronomical societies. There are nine principal centers of amateur observing, which are enumerated below, together with some indication of the principal type of observation that they contribute, and the manner in which the observations are made available.

The first three associations, in particular, have members scattered over the globe, in latitude as well as in longitude; thus the

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[8] Handbuch d. Astrophysik, 6, 103, 1928.
[9] Ludendorff, Sitz. d. Preuss.Ak. d. Wiss., 20, 3, 1932.
[10] Townley, Cannon, and Campbell, *op. cit.*

Organization	Headquarters	Principal Type of Observation	Publication
American Association of Variable Star Observers	Harvard College Observatory	Long-period variables; SS Cygni and R Coronae Borealis Stars	Popular Astronomy (1911-1935); Harvard Annals; Own Publications ("Variable Comments")
British Astronomical Association, Variable Star Section		Long-period variables	Journals Memoirs, and Handbook, of the B. A. A.
L'Association Francaise D'Observateurs D'Etoiles Variables	Observatoire de Lyon, St. Genis-Laval, France	Long-period variables	Bulletin
Astronomisk Selskab	University Observatory, Copenhagen, Denmark	Long-period variables; SS Cygni stars	
Observing Corporation of the Society of Amateur Astronomers of Moscow	Moscow, U.S.S.R.	Long-period variables; Cepheids	Bulletin
Russian Society, "Mirovedenie"; Astronomical Section	Leningrad, U.S.S.R.	Long-period variables	Publications
New Zealand Astronomical Society; Variable Star Section	Wellington, New Zealand	Long-period variables; Cepheids	Variable Star Section Circulars
Japanese Astronomical Society	Mitaka-mura near Tokyo	Long-period variables; SS Cygni, R Coronae Borealis stars	Astronomical Herald
Young Generation Club of the Czech Astronomical Society	Prague, Czechoslovakia	Long-period Variables	Astronom Amater
Amigos de la Astronomia	Buenos Aires, Argentina	Long-period Variables	Revista Astronomica

southern skies are covered as well as those of the north, although not to the same satisfactory extent.

Mention should also be made of the more extensive and important series of unpublished observations of long-period variables. They have been assembled in a list compiled by Grouiller, under the auspices of the International Astronomical Union, which body has also undertaken its publication.

A survey of the "Katalog und Ephemeriden", or even of the Harvard "Catalogue of Long-Period Variables" reveals a bewildering number of stars belonging to the class; but often our knowledge of individuals is confined to the period and the magnitude at maximum. For anything but the most general statistical purposes it seems useful to have a shorter list of long-period variables, all of which are relatively well observed. Such a list is contained in Table III, I. Successive columns of the table contain the name of the star, the designation*, the galactic longitude and latitude, the apparent magnitude at maximum† (italicized if photographic), the range†, the period†, the spectrum (or spectra, if variable),† the radial velocities from absorption and emission lines,[11] the classifications of the light curve by Campbell‡ and by Ludendorff,[12] and the measured characteristics of the light curve, obtained as mentioned in the next section. No star has been admitted to the table unless the spectrum is known and the light curve has been classified with some certainty. Exceptions have been made for a few stars of uncommon spectrum or light curve, and all stars of known radial velocity have been included. Numbers in a final column refer to notes, at the end of the table, which make mention of special studies, chiefly spectroscopic, that have been made of

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*Conveying the approximate 1900 position: for instance, a star at $13^h\ 54^m\ 14^s$, $+\ 28°\ 53'$, would receive the designation 135428; and one at $2^h\ 8^m\ 52^s$, $-\ 88°\ 2'$ would receive the designation 0208*88*.

† Where the values of these quantities are not the same as those given in the "Katalog und Ephemeriden" for 1936, they are unpublished values, kindly furnished by Mr. Campbell, or are taken from the Harvard "Catalogue of Long-Period Variables," or No. 24 of Harvard Annals, Vol. 105, 1936.

‡ Unpublished material furnished to the authors.

[11] Merrill, Mt. W. Contr. 264, 1923.

[12] Ludendorff, Sitz. d. Preuss. Akad. d. Wiss., Phys.-Math. Kl., 20, 3, 1932.

particular stars. It should be noted that a few of the stars with periods less than a hundred days, given in this table, such as RU Velorum, are also contained in Table V, I.

28. Classification of Light Curves.—The number of long-period variables is large and therefore many attempts have been made to subdivide them. The most obvious method of classifying them is by means of their light curves. Since 1904, when Turner first published a classification of nineteen long-period variables, there have been more than half a dozen attempts that merit discussion. The early history of the classifications has been adequately described by Ludendorff[13] and by Thomas[14], and here we shall merely summarize the chief points of the various systems.

The earlier methods were of an analytical nature, both Turner[15] and Phillips[16] basing their classifications on harmonic analyses of the light curves and attempting to correlate other properties of the stars with the constants so derived. It appears that the inherent variability of the light curves introduces great difficulties for such a system, which is actually too precise for material of this nature.

Another type of classification reposes on a more qualitative estimate of the shape of the light curve. The first step was taken by Campbell[17], who laid down the foundations for the present Harvard system of classifying light curves[18]. The contributions of Hagen[19] and Hassenstein[20] lent weight to the practice of classifying light curves by means of their general appearance. A somewhat broader basis was adopted by Jacchia[21], who used the spectrum as an additional parameter, and formed three classes, named respectively for their prototypes,

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[13] Handbuch d. Astrophys., 6, 92, 1928.

[14] Veröff. Berlin-Babelsberg, 9, No. 4, 1932.

[15] Mem. R.A.S., 2nd Series, p. 98, 1904; M. N., 64, 543, 1904; *ibid.*, 67, 332, 1907; *ibid;* 78, 371, 1919.

[16] J.B.A.A., 27, 2, 1916.

[17] H.A., 57, 1, 1907.

[18] H. Repr. 21, 1925.

[19] M. N., 79, 572, 1919; A. N., 209, 257, 1919; Ap. J., 53, 179, 1921; Die Veränderliche Sterne, Vol. I, 1921.

[20] A. N., 219, 373, 1923; *ibid.*, 221, 385, 1924.

[21] Bologna Obs. Publ., 2, 211, 1933.

Mira Ceti, X Monocerotis, and R Leporis. Other classes of long-period variables have been formed in the same spirit by Lundmark,[22] to comprise stars that resemble Betelgeuse and Mira Ceti; Ludendorff[23] has suggested a class of R Centauri stars. But the naming of too many classes after individual stars is likely to lead to confusion and misunderstanding, and an objective basis of classifying is much to be preferred.

In the list of long-period variables (Table III, I) are given the classifications of the light curves on the systems of Campbell[24] and of Ludendorff[25], and therefore both these systems will now be briefly described.

i. *System of Ludendorff.*—Three chief classes embrace all the observed types of light curves for long-period variables:

α. The rise is much steeper than the fall in brightness; the minimum is broader than the maximum; α_1, α_2, α_3, α_4 represent a continuous decrease in steepness of rise and in width of minimum.

β. The light curve is more or less symmetrical; β_1, β_2, and β_3 are subdivisions according to increasing width of maximum.

γ. The light curve shows constant brightness over an interval during the rise; or a hump or a secondary maximum occurs; γ_1, γ_2 distinguish the former from the latter. In addition, the subdivision α_2–γ_1 denotes a light curve of type α_2 with a hump on the rising branch, and similarly for such combinations as: α_3–γ_1, α_4–γ_1, β_1–γ_1, β_2–γ_1, and β_3–γ_1. Thus the classification provides for eighteen subdivisions.

ii. *System of Campbell.*—Campbell's criteria may be summarized as follows:

Classes:	A	Maximum broader than minimum.
	B	Maximum and minimum more or less equal.
	C	Minimum broader than maximum.
	D	Secondary maximum (or minimum).

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[22] Pop. Astr. Tidsk., 3, 87, 1932.

[23] A. N., 220, 148, 1924.

[24] Revised system kindly communicated personally to the writers.

[25] Handbuch der Astrophysik, 6, 99, 1928; revised, Sitz. d. Preuss. Akad. d. Wiss., Phys.-Math. Kl., 20, 3, 1932; Handbuch d. Astrophys., 7, 627, 1934.

Secondary classes:	a	Rise equal in speed to fall.
	b	Rise steeper than fall.
	c	Fall steeper than rise.
	d	Light curve with a bump, a hump, or a constant brightness, usually on the rise.

Thus Campbell's classification provides for thirteen possible groups. It need hardly be mentioned that both Ludendorff's and Campbell's classifications are made from inspection of the light curves. The two systems overlap in many respects, but it may be seen from Table III, I that they are not closely correlated in all cases. The most frequent class of light curve is Campbell's C (Ludendorff's β).

iii. *Numerical parameters.*—The essential quantities expressed by all systems of classifying light curves are: (a) asymmetry with respect to the ordinate (speed of rise and fall); (b) asymmetry with respect to the abscissa (duration of maximum or minimum), and (c) existence of a secondary minimum or bump. For purely descriptive purposes, classes such as those of Campbell and Ludendorff are excellent. It is only difficult to keep in mind so many symbols and their meanings. But their classifications relate only to long-period variables; in fact Ludendorff in his classification of the Cepheids[26] deliberately used a different notation, and somewhat different criteria, from those that he used for the long-period variables. The difficulty just mentioned thus increases. But as the present work is concerned with the relationship between the members of the Great Sequence (the long-period variables, Cepheids, and cluster-type stars) we have introduced, in addition, *three numerical* parameters to describe the light curves. The light curve is described by three numbers, the ratios a/b, c/d, and e/f. The ratio a/b is the ratio of the two parts of the light curve indicated by those letters in Figure III, 1, reckoned from minimum to maximum, and from maximum to minimum, respectively. The ratio c/d expresses the ratio of the two areas enclosed between the light curve and a straight line, parallel to the axis of abscissae, drawn

[26] Sitzber. d. Preuss. Akad. Wiss., Phys.-Math. Kl., 5, 1929.

through the median magnitude. The ratio *e/f* is the ratio of the two time intervals (minimum to preceding bump/minimum to preceding maximum); if there are two or more bumps on the light curve, two or more values of *e/f* can be given for that light curve. In practice, in the tables where they are given, these ratios have been multiplied by ten. Our ratios *a/b* and *c/d* have much resemblance to the parameters used first by Thomas[27], and again by de Kock;[28] since the work of these authors it has been recognized that in discussing correlations with other properties, numerical values have an advantage over formal classifications. They can be determined, for instance, for quite unrelated stars such as novae.

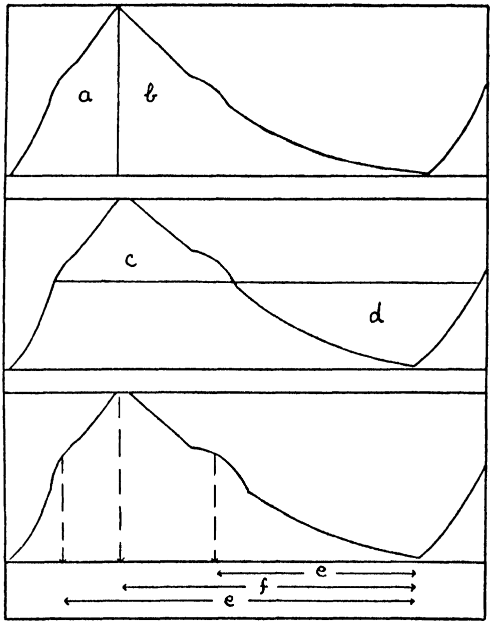

Figure III, 1.—Parameters for describing the light curve: *a/b*, *c/d*, and e/f. From S. Gaposchkin, P.N.A.S., 24, 1, 1938.

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[27] Die Langperiodischen Veränderlichen, Veröff. Berlin-Babelsberg, 9, No. 4, 1932.

[28] Utrecht Astr. Obs., Res., No. 10, 1933.

The quantity a/b is closely correlated with the quantity $(m-M)/P$, which has been extensively used to characterize Cepheid and sometimes long-period variables. But $(m-M)/P$ is a less precise quantity, especially for light curves in which the minimum brightness is more or less constant, and the location of the actual minimum therefore subject to large error. The ratio a/b gives a definite measure of the steepness of the light curve, independently of the character of the minimum. A light curve that shows several waves is not covered by our scheme, but fortunately such light curves are exceptional. All the systems of classification that we have adopted apply primarily to light curves that are smooth and regular.

It follows from what has been said, that if $a/b = 1$, and $c/d = 1$, the light curve is symmetrical. The descriptions conveyed by various values of the three ratios are summarized below:

$10 \times a/b=10$: rise and fall of equal steepness
$a/b<10$: rise faster than fall
$a/b>10$: rise slower than fall
$c/d=10$: maximum and minimum of equal width
$c/d<10$: maximum narrower than minimum
$c/d>10$: maximum broader than minimum
$e/f>10$: hump on the rising branch
$e/f<10$: hump on the declining branch

The numerical ratios have the advantage of expressing stages intermediate between all the main classes; and a further advantage, that their mean value can be taken, whereas if named classes are used, their frequency must be studied.

After an investigation of the published light curves of about a thousand members of the Great Sequence (including variables in globular clusters), we conclude that the average values of a/b and c/d differ considerably from class to class. Thus from 424 long-period variables we obtain the mean values: $10\ a/b=8.3$; $10\ c/d=8.0$. In other words, the mean light curve for these long-period variables is not very far from symmetrical; but the case is quite different for the average Cepheid variable.[29]

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[29] See Section 32, ii.

It is a well-known fact, pointed out by most of the investigators previously cited, that among the long-period variables the asymmetry of the light curve progresses with the period. The following table shows the relation of our three ratios to period for 277 long-period variables. It is of interest to note that out of 49 stars with humps on the light curve, only five show a hump on the descending branch. The establishment of a hump, however, requires high precision in the observations, and only in the last ten years has attention been paid to this property of the long-period variables, or the stars of the Great Sequence in general.

TABLE III, II

RELATION OF FORM OF LIGHT CURVE TO PERIOD

Interval of Period	10 *a*/*b*	No. of Stars	10 *c*/*d*	No. of Stars	10 *e*/*f*	No. of Stars
d *d*						
100–149	9.5	10	11.0	10	20	2
150–199	9.7	15	10.5	15	21	2
200–249	9.3	42	9.5	42	20	1
250–299	8.9	67	8.9	67	19	4
300–349	8.9	67	8.6	67	23, 8	13, 2
350–399	8.6	42	8.6	42	22	14
400–449	7.0	17	6.8	17	24, 7	7
450–499	7.5	8	6.5	8	26	3
500–549	5.3	6	5.7	6	25, 6	2, 2
>550	5.2	2	5.0	2	25	1

We may refer to the paper quoted on page 94, in which the conclusion has been drawn that the hump on the ascending branch for a long-period variable is nearer to the minimum the longer the period, that the hump on the descending branch seems to show the opposite direction, and that asymmetry of the light curve increases rapidly for the periods over 320^d.

Table III, II evidently confirms these results.

We shall not now enter upon a detailed study of the relation of the measured parameters of the light curves to other properties of the stars, as has been done by Ludendorff[30]; the relation established in Table III, II will connect the asymmetry with the other properties that are known to be correlated with the period. In the chapter on Cepheid variables it will be shown that within that group also the measured parameters of the light curve bear a close relation to the period.

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[30] Sitz. d. Preuss. Akad. Wiss., Phys-Math. Kl., 20, 3, 1932.

29. General Characteristics of Long Period Variables.—There are probably more data, in and outside the literature, about long-period variables than about any other type of variable star, and it is manifestly not possible to summarize them all, even in outline, in a treatment such as the present. A survey of many aspects of the subject, but with especial stress on physical and spectroscopic data, has been made by Merrill[31] in a series of papers (which constitute a brief general monograph on the group) and in a book that summarizes the content of the papers and treats briefly of some other matters.

In the face of so rich a collection of data, the compiler is forced to make a selection and arrangement, in accordance with his own opinions or conclusions as to the significance of the facts. Significance must be measured from a chosen aspect; and because in the present volume we seem only to be ready to consider the relationships of the groups of variable stars to one another (as a necessary preliminary to the still distant consideration of the cause, nature, and mode of their variation), the aspects here selected are those that permit us to make comparisons with the other types of variable stars, notably the Cepheids. What little can be said about the actual physical processes that are going on, depends essentially on the results of this comparison: are the long-period variables and the Cepheids strictly comparable and merging series of stars; or are they separated by a hiatus; or are they parallel groups?

i. *The Period-Spectrum Relation.*—There is a well-marked relation between period and spectral class for the long-period

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[31] Merrill, Pop. Astr., 37, 60, 1929: The Nature of Variable Stars; *ibid.*, 37, 253, 1929: The Discovery of Long Period Variable Stars; *ibid.*, 37, 444, 1929; The Spectral Classification of Long Period Variable Stars; *ibid.*, 39, 121, 1931: The Light Curves of Long Period Variable Stars; *ibid.*, 41, 188, 1933: The Motions of Long Period Variable Stars; *ibid.*, 42, 180, 1934: Physical Characteristics of Long Period Variable Stars; *ibid.*, 43, 214, 1935: Theories of Long Period Variable Stars; *ibid.*, 44, 62, 1936: Long Period Variable Stars and the Stellar System; The Nature of Variable Stars, MacMillan, 1938.

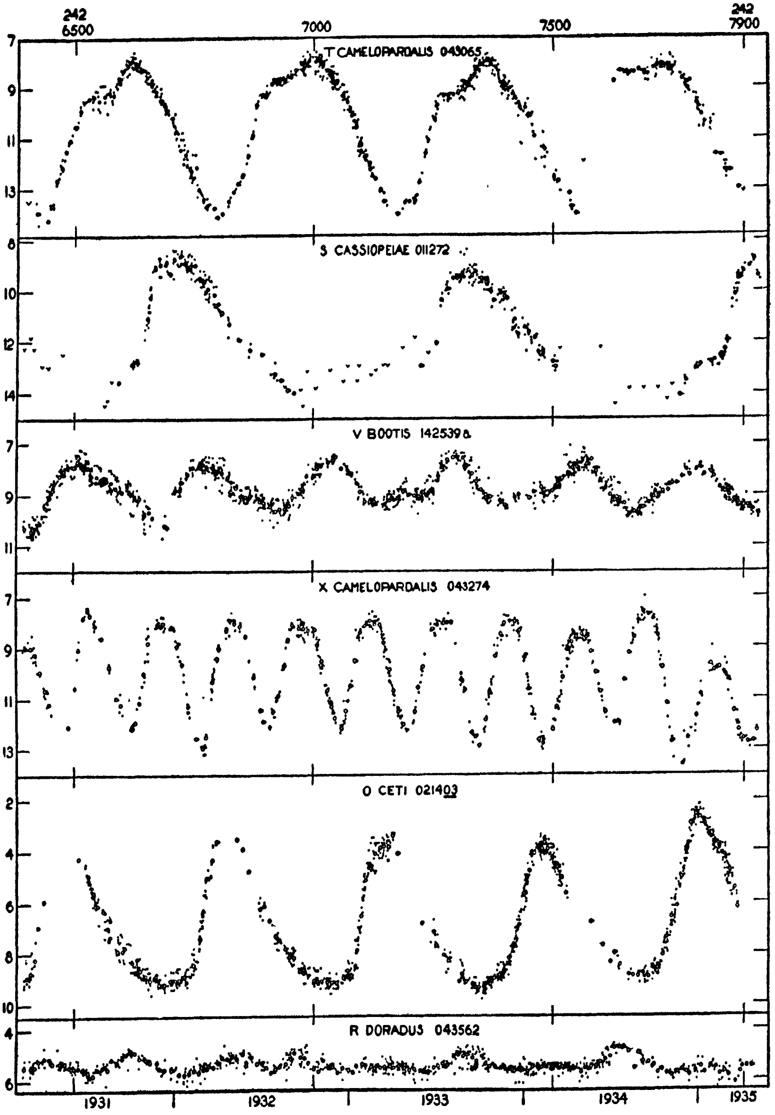

Figure III 2.—Light curves of six long-period variables, from visual observations made by the A.A.V.S.O. and other groups of observers. From Campbell, Harv. Repr. 132, 1937, reproduced with his kind permission.

variables, as there is for the Cepheids[32]. In the latter group, the relation is relatively uncomplicated, but among the long-period variables three quantities (period, spectrum, and range) are interrelated in such a way that the longest periods are associated jointly with the latest spectra and the largest ranges[33]. The data given by Campbell and Cannon in their discussion of the Harvard "Catalogue of Long Period Variables" are still representative of the three-way relationship for Me stars, and are reproduced in Table III, III. Subsequent additions to the data on period, spectrum, and range would make small numerical changes, but the essential character of the relationships for Me stars is sufficiently conveyed by the table. The addition of the few stars with periods less than 100 days would scarcely affect the tabular entries; the average spectrum for three such stars with Me spectra is M2.6e, the average range $3^m.3$.

TABLE III, III

RELATION BETWEEN SPECTRUM, PERIOD, AND RANGE

Spectrum	Mean Periods	No. of Stars	Mean Range	No. of Stars	Period	Mean Spectrum	No. of Stars	Mean Range	No. of Stars
M0e	137	1	2.7	5	100–149	M2.4e	20	2.9	15
M1e	158	5			150–199	M3.0e	35	3.4	32
M2e	219	32	4.4	26	200–249	M3.3e	61	4.5	49
M3e	242	86	4.5	65	250–299	M3.8e	79	4.6	69
M4e	292	77	4.5	64	300–349	M4.9e	91	4.8	75
M5e	308	62	4.7	53	350–399	M5.8e	50	4.9	40
M6e	343	69	4.3	61	400–449	M6.3e	31	5.0	25
M7e	392	47	4.9	37	450–499	M5.9e	9	4.8	8
M8e	446	2			500–549	M6.4e	5	5.1	4

There can thus be little doubt that period, spectrum, and range are correlated for long-period Me stars, regarded as a single group; but as will be shown later, there are other reasons for surmising that the assumption that the long-period variables are a single group is not altogether justified.

If the period-spectrum relation given in Table III, III is compared with that for Cepheids (Table IV, III) it appears that the two form parts of one series, but that they seem to be separated by a hiatus—the Cepheids of period so long as to overlap with the short-period end of the curve for long-period variables do not fit the period-spectrum relation, and it seems that there is some justification for assuming the existence of more than one group of stars in this class also.

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[32] Shapley, H. B. 861, 1928; *cf.* Adams and Joy, Mt. W. Comm. 100, 1927.
[33] Campbell and Cannon, H. B. 862, 1928.

The fact that the long-period variables fit the average period-spectrum relation for the classical Cepheids (at least those of shorter period) is the chief support of those who consider that the variation is of the same type for the two kinds of stars.

ii. *The Relation of Period to Light Curve.*—The measures of the form of the light curve, given in the thirteenth and fourteenth columns of Table III, I, are related to period in Table III, II. The relationship is evident, and may also be seen from the more qualitative classifications of Campbell and Ludendorff[34].

The numerical classifications made in the present chapter have for their chief object a comparison of long-period variables and Cepheids. The corresponding tables for Cepheids (Table IV, I; IV, II) show that, although there is also an evident relationship between period and form of light curve for them, it is not continuous with the relationship for long-period variables. The great difference in range for the two groups of stars may be responsible for the break in the relation between period and *c/d*, but the break in the relation between period and *a/b* cannot be explained in this way.

iii. *The Period-Luminosity Relation.*—Our knowledge of the period-luminosity relationship among the long-period variables is chiefly indirect. No long-period variables have been discovered in the external systems, even including the Magellanic Clouds. It is conceivable, but improbable, that they are actually absent from such systems. The possibility that, though present and accessible, they have been overlooked can be dismissed when we recollect that careful surveys for variable stars have been made[35] of the spiral nebulae Messier 31 (probably more or less comparable in population with our own galaxy) and Messier 33; and of the irregular systems, the Large and

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[34] Sitz. d. Preuss. Akad. d. Wiss., Phys.-Math. Kl., 20, 3, 1932.

[35] Hubble, Mt. W. Contr. 452, 1932.

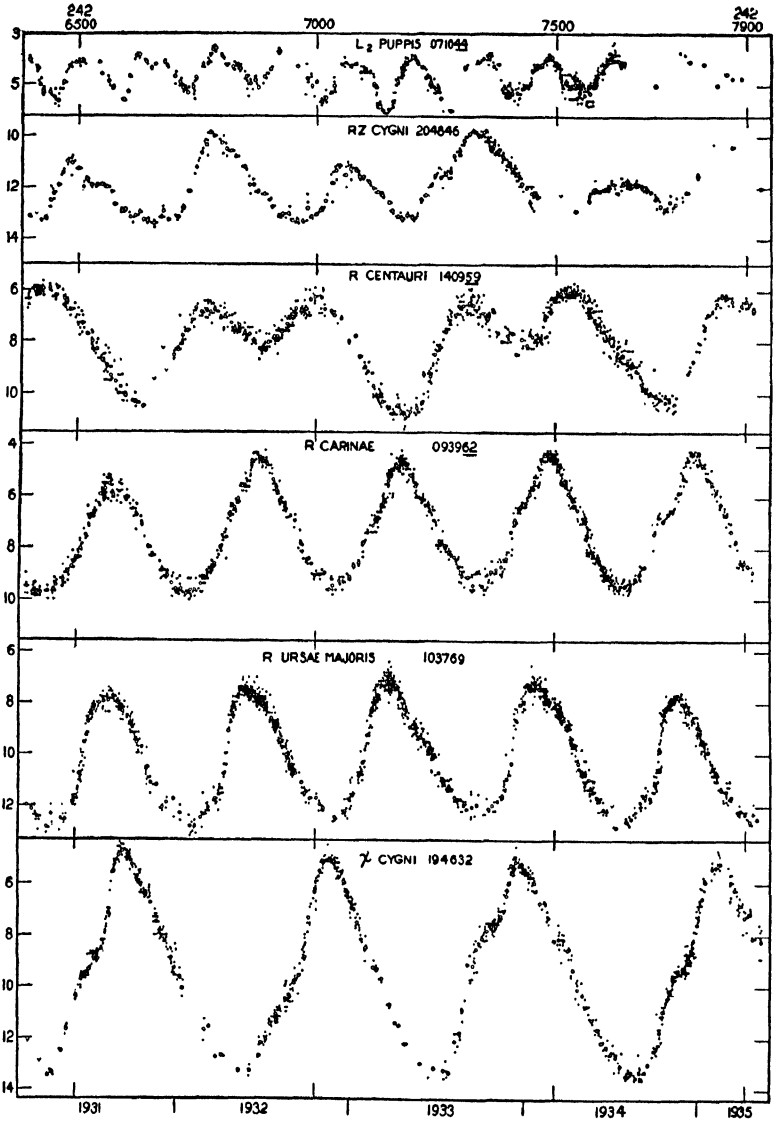

Figure III, 3.—Light curves of six long-period variables, from visual observations made by the A.A.V.S.O. and other groups of observers. From Campbell, Harv. Repr. 132, 1937; reproduced with his permission.

Small Magellanic Clouds[36], and N. G. C. 6822[37]. For Messier 31, if we assume a distance modulus (*M–m*) of $22^m.5$ and a limiting maximum apparent magnitude for variable stars of 19.0, long-period variables must be absolutely fainter photographically than —3.5; for the Small Magellanic Cloud, with an assumed modulus of $17^m.5$ and a limiting maximum apparent magnitude of 17, they must be absolutely fainter photographically than —0.5. The shortest period and faintest Cepheid in Messier 31 has a period of ten days and a median apparent photographic magnitude of 19.7; thus we may conclude that if there are long-period variables in Messier 31, they are fainter photographically even than a Cepheid of period ten days, and must therefore fall far below the *photographic* period-luminosity curve as defined by the Cepheids, considerably below even the visual period-luminosity curve.

The negative evidence afforded by the external galaxies can be supplemented by positive evidence from the globular cluster 47 Tucanae, which contains three long-period variables[38]. The variables are apparently normal, with an average range of three magnitudes, and are all of about the eleventh photographic magnitude at maximum, leading (from the parallax of the cluster estimated in well-established and reliable ways) to an absolute photographic magnitude[39] not greater than —2.0.

Similar results were derived by Shapley from a comparison of the apparent photographic magnitudes of the long-period variables and the cluster-type stars discovered by Miss Swope[40] in the field of stars seen toward the galactic center, and assumed to be members of the same star cloud[41]: on the average the long-period variables at maximum were one magnitude brighter photographically than the median magnitude of the cluster-type variables, leading to an average absolute photographic magnitude of —1.0, or an absolute visual magnitude of about —2.5. It should be noted that the average period of the three

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[36] See Shapley, H. A., 90, 1, 1933.
[37] Hubble, Mt. W. Contr. 304, 1925.
[38] Shapley, H. B. 783, 1923.
[39] Shapley, P. N. A. S., 14, 958, 1928.
[40] Swope, H. B. 857, 862, 1928.
[41] Shapley, P. N. A. S., 14, 958, 1928.

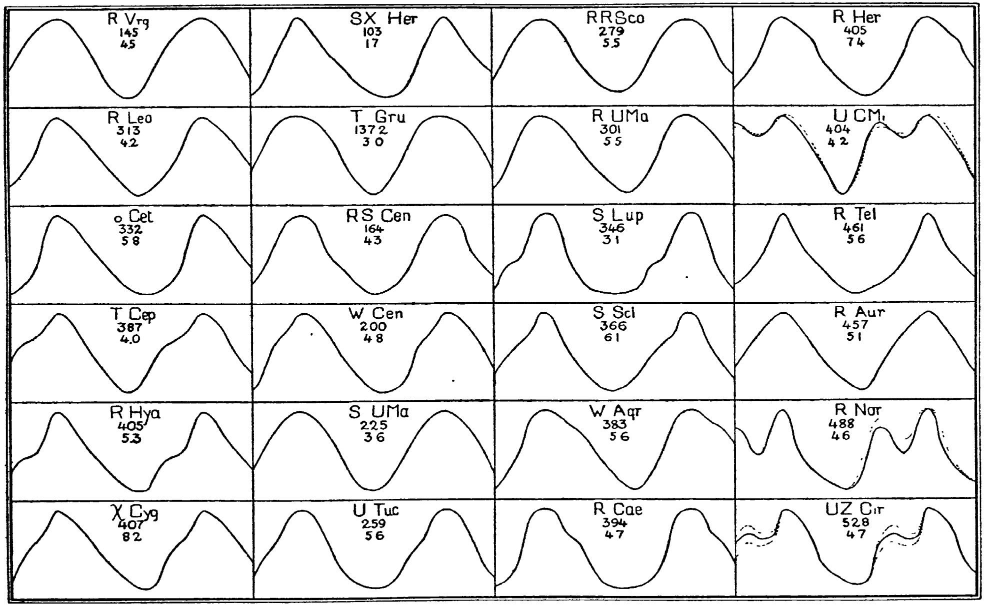

Figure III, 4.—Light curves of 24 typical long-period variables. The curves for R Virginis, R Leonis, o Ceti, T Cephei, R Hydrae, χ Cygni, and the broken curve for R Normae, are from mean light curves derived from visual observations made by the A.A.V.S.O., compiled and kindly supplied by Leon Campbell. Other sources are as follows: SX Herculis (photographic), Gerasimovič, H.B. 869, 1929. U Canis Minoris (broken curve, visual), Jacchia, Publ. Obs.Astr.Univ. Bologna, 2, No: 14, 1933. UZ Circini (photographic), Miss Swope, H.B. 883, 1932. Other curves are from mean photographic light curves derived from Harvard plates.

All the light curves are reduced to the same scales of ordinates and abscissae. The periods (days) and the ranges (magnitudes) are indicated below the names of the stars in the diagram. With the exception of those in the first column, the light curves are arranged in order of increasing period.

long-period variables in 47 Tucanae is about equal to the average period (approximately 225 days) for the long-period variables near the galactic center. But Shapley, in discussing all the long-period variables discovered toward the galactic center, noted that there appeared, for those stars at least, to be no relationship between apparent magnitude and period, and in commenting on the difference between this result and the results of statistical investigations of luminosities and periods, he made the suggestion that there may be more than one group of long-period variables—a suggestion that has since found considerable support. For example, in the Cygnus cloud, situated in a different part of the sky, Baade[42] noted an evident relation between period and apparent photographic magnitude, in the sense that the stars of shortest period are the brightest.

The statistical discussions of the absolute magnitudes of long-period variables lead to results that are not in conflict with the foregoing. Merrill and Strömberg[43] deduced a mean absolute visual magnitude +0.1 for all available Me stars, the brightness decreasing from $-0^m.6$ for Class M2e to $+0^m.6$ for Class M8e; since early spectrum is correlated with short period, the more luminous stars were thus those of shorter period. Oort,[44] discussing all available Me stars together, obtained an average absolute visual magnitude of −2.0. Gyllenberg[45], discussing absolute magnitude at minimum, derived a period-luminosity curve for which the stars of shorter period were the most luminous. Lastly, Gerasimovič[46], rediscussing and supplementing the material used by Oort, derived the results contained in Table III, IV.

The figures in the third column are the absolute magnitudes derived by Gerasimovič, who commented: "This constitutes a 'period-luminosity relation' for long period variables, which is not necessarily a direct continuation of Shapley's law for Cepheids, because the changes in absolute visual magnitude for long period variables are probably chiefly the result of

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[42] Baade, Mt. W. Contr. 493, Table II, 1934.

[43] Mt. W. Contr. 267, 1924.

[44] Oort, B. A. N., Nos. 120 and 132, 1927.

[45] Gyllenberg, Lund Medd., Series 2, No. 53, 54, 1929.

[46] P. N. A. S., 14, 963, 1928.

Table III, IV

Period and Luminosity for Long-Period Variables

			Corrected for Band Absorption	
Group	Period Limits	Absolute M_{vis}	I	II
			m	*m*
I	90–250	−2.3	−2.5	−3.6
II	251–340	−1.1	−2.1	−3.3
III	340	+0.3	−1.7	−2.5

redistribution of light by the absorption bands." The fourth and fifth columns are derived by the use of two different corrections for band absorption: the first is taken from the paper of Gabovitč and Opik[47] on the densities of visual double stars, and the second is derived from Hetzler's infra-red light curves.[48] The effect of both of the corrections for band absorption is to remove the relation between period and visual brightness, and the suggestion is that if an appropriate correction is made for absorption and redistribution of light by TiO bands, there is no relation between period and brightness among the long-period variables. In earlier discussions of the subject by one of the authors[49], the magnitude of the titanium oxide absorption seems now to have been overestimated, and part of the role previously assigned to it is probably played by another process[50].

Even when extreme values for the titanium oxide absorption were postulated, the long-period variables could not be brought onto the bolometric period-luminosity curve as defined by the Cepheids; and at present we must consider that they lie between three and four magnitudes below it. It must be remembered that the long-period variables may not be a homogeneous group, and that they may embrace a variety of absolute magnitudes.

[47] Tartu Publ., 28, No. 3, 5, 6, 1935; the authors state that the values are "undercorrections".

[48] Ap. J., 83, 372, 1936.

[49] Payne, The Stars of High Luminosity, 225, 1930; Payne and ten Bruggencate, H. B. 876, 1930; *cf.* Merrill, Pop. Astr., 43, p. 219, 1935.

[50] See Merrill, Pop. Astr., *op. cit.;* Shajn, M. N., 94, 642, 1934; Wildt, Zs. f. Ap., 6, 345, 1933.

iv. *Distribution of Long-Period Variables and Frequency of Periods.*—The distribution of 1719 long-period variables in galactic latitude is summarized in Table III, V. It appears that there is considerable galactic concentration, probably accentuated by the fact that low galactic latitudes have been preferentially searched for variable stars.

TABLE III, V

GALACTIC LATITUDES OF LONG-PERIOD VARIABLES

Limits of Latitude	No. of Stars = N	$N \sec \bar{\delta}$
° °		
±81–90	8	90
71–80	17	67
61–70	31	97
51–60	60	100
41–50	86	120
31–40	126	154
21–30	230	255
11–20	535	550
0–10	636	636

For the purpose of studying the distribution in galactic longitude, the galactic sphere was divided into four quadrants, as follows: I, 11°–100°; II, 101°–190°; III, 191°–280°; IV, 281°–360°–10°. These quadrants are so chosen that the galactic center ($\lambda=325°$) lies in the middle of the fourth. The center of the Local System ($\lambda=275°$, $\beta=0°$) falls within the third. A discussion of 1003 long-period variables (all those belonging to the class and with periods determined, contained in the Harvard Catalogue of Long-Period Variables) leads to the distribution in galactic longitude shown in Table III, VI.

TABLE III, VI

GALACTIC LONGITUDES OF LONG-PERIOD VARIABLES

	Quadrant	I	II	III	IV	Total
Latitude	>±30°	71	44	51	83	249
	<±30°	224	122	91	317	754
All		295	166	142	400	1003

It is noticeable that the greatest frequency of long-period variables is found in the fourth quadrant, the smallest in the third (especially when low latitudes are considered); a comparison with the Cepheids is instructive, since for them (latitudes less than 30°) the results are as follows: I, 54; II, 44; III, 95; IV, 76, with the greatest frequency in the third quadrant. In other words, Cepheids are commonest where long-period variables are rarest — another respect in which the two types of star appear to differ.

A further analysis of the distribution of long-period variables brings out the striking fact that the frequency of periods is widely different in the four quadrants. Table III, VII analyzes the data for 991 long-period variables — those of Table III, VI, with the exception of twelve stars with periods less than 100 days, one in the first quadrant, eleven in the fourth.

TABLE III, VII

FREQUENCY OF PERIOD AS A FUNCTION OF GALACTIC LONGITUDE

	Period	100-150	151-200	201-250	251-300	301-350	351-400	401-450	451-500	500	Sum
Quad.	Lat.										
I	>+30°	2	2	10	9	9	3	0	0	0	
	<+30°	5	9	18	22	18	10	8	4	4	
	<−30°	14	8	19	20	30	12	17	4	2	
	>−30°	2	6	7	3	7	8	1	1	0	
	Sum	23	25	54	54	64	33	26	9	6	294
II	>+30°	2	2	4	5	3	2	1	1	0	
	<+30°	6	4	8	13	15	10	4	4	4	
	<−30°	7	5	7	9	13	6	4	1	2	
	>−30°	1	5	3	4	6	4	1	0	0	
	Sum	16	16	22	31	37	22	10	6	6	166
III	>+30°	1	2	4	2	6	3	2	0	1	
	<+30°	0	3	4	8	8	5	5	1	0	
	<−30°	5	7	7	10	15	8	4	0	1	
	>−30°	0	3	9	6	6	3	3	0	0	
	Sum	6	15	24	26	35	19	14	1	2	142
IV	>+30°	3	3	5	5	5	7	1	1	0	
	<+30°	3	13	23	15	16	9	6	1	1	
	<−30°	9	17	73	55	27	22	10	5	2	
	>−30°	2	1	17	15	10	4	2	1	0	
	Sum	17	34	118	90	58	42	19	8	3	389
I–IV		62	90	218	201	194	116	69	24	17	991

From Table III, VII, it is evident that whereas in the first three quadrants the maximum frequency of periods falls between 300 and 350 days, in the fourth the most frequent period is about one hundred days shorter. It is this second group of variables, which is concentrated in the direction of the galactic center, that gives to the frequency of periods the bimodal form already noted by Campbell and Cannon[51]. Thus, the variables of longer period (greater than 250 days) are distributed more or less uniformly in longitude, save for the deficiency in the third quadrant already mentioned; perhaps this group also includes some stars of shorter period. In addition, there seems to be a group with an average period not much greater than 200 days, that lies in the direction of the galactic center.

The discussion just made was based on the Harvard Catalogue of Long-Period Variables, because that catalogue contains fairly homogeneous material, and in particular does not include the results of the recent intensive searches for variable stars in low galactic latitudes. But the results of those searches amplify and corroborate the conclusions drawn from the brighter stars.

Most of the Harvard studies of faint galactic variables in "Milky Way Fields" (about twelfth magnitude at maximum) that have hitherto been completed refer to the fourth quadrant, but three (MWF 167, 168, and 169) fall in the third. Results from these regions, and from the fourth-quadrant regions MWF 184, 185, 187, 193, and 233 are summarized in Table III, VIII.

The two main features of the previous table are repeated in the present one, and clearly the phenomenon is not entirely confined to the brighter stars — in other words, the maximum frequency of period seems to be a function of the galactic quadrant. But for the sum of the fourth-quadrant fields the suggestion of a bimodal frequency distribution has disappeared, as though with the twelfth and thirteenth magnitude stars toward the galactic center we had reached a region where the group of long-period variables with a maximum frequency of

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[51] H. B. 862, 1928.

TABLE III, VIII

FREQUENCY OF PERIODS FOR FAINT MILKY WAY VARIABLES OF LONG PERIOD

		50–100	101–150	151–200	201–250	251–300	301–350	351–400	401–450	451–500	500
Quad. III											
MWF	167	0	2	11	9	13	1	0	0	1	0
	168	0	1	0	2	3	6	6	3	1	2
	169	2	7	11	14	14	8	2	6	1	1
	Sum	2	10	22	25	30	15	8	9	3	3
Quad. IV											
MWF	184	3	9	36	47	40	13	9	4	1	0
	185	3	10	10	10	5	11	13	5	0	0
	187	4	25	29	69	59	13	4	9	3	2
	193	0	0	6	4	6	0	0	0	0	0
	233	0	5	12	22	27	8	4	1	1	1
	Sum	10	49	93	152	131	45	30	19	5	3

period of 325 days is no longer present in significant proportions.

The rarity of long-period variables in the third quadrant must be real, for the Cepheids, which are both more distant and more difficult to establish, have their maximum frequency in that direction.

v. *Radial Velocities.*—The problems presented by the radial velocities of long-period variables are discussed in general terms by Merrill in his article dealing with "The Motions of Long Period Variable Stars"[52]. He says: "Variables with earlier types (M1-M4) and shorter periods have the higher velocities. The correlation between period and velocity is incomplete in that stars of low velocity may have any period, but it is remarkable that very high velocities are largely confined to stars having periods between 150 and 250 days". In other words[53], decreasing random velocity is another quantity that follows the same progression as advancing spectral type, increasing period, and increasing magnitude range. In addition, Merrill points out[54] that increasing displacement of bright lines, relative to absorption lines, follows the same progression. Stars of Classes N and S show similar relative displacements, which are correlated with period for the latter. A list of the radial velocities, derived at Mount Wilson and elsewhere, is given for 133 long-period variables in Mount Wilson Contribution 264; the velocities will be found in our Table III, I.

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[52] Pop. Astr., 41, 188, 1933.

[53] Merrill, Mt. W. Contr. 264, 1923.

[54] Merrill, Mt. W. Contr. 264, 47, 1923.

It may be said that no interpretation that covers the various progressions discussed in the preceding five sections has been suggested as yet. Perhaps the most significant fact, from the standpoint of the other correlations, is that the stars with periods of about two hundred days are singled out by excessive velocity, as well as by position in the sky; at least two groups of long-period variables seem to be indicated. If, as Merrill suggests[55], the difference of radial velocity has an evolutionary significance, the difference of frequency of period, as a function of galactic position, probably has no less a significance. The velocities of R and N stars have been discussed by Sanford[56], who shows that the difference between absorption and emission velocities (21.6 km/sec) is greater than the extreme value found by Merrill (M1e, −3; M8e, −20), and tabulates differences for eleven stars.

30. **Properties of Individual Stars.**—The best observed long-period variables are enumerated in Table III, I, which contains in condensed form descriptions of the light curves and of the spectral variations and motions. Perhaps the best illustration of the processes that constitute long-period variability is furnished by the typical stars, whose variations are shown by Merrill in Mount Wilson Contribution 399, Figure 17. It is difficult to come to a definite conclusion as to the relationship of light curve to velocity curve for long-period variables. The phase relationship is definitely different from that shown by the Cepheids.

i. *Spectra and Spectral Changes; Class Me.*—The greatest mass of general information concerning the spectra and spectral changes of long-period variables is contained in Miss Cannon's classifications of their individual spectra.[57] The spectrum is variable throughout the light cycle, the spectral class, as indicated by the absorption bands, being earliest at maximum, latest at minimum, as in the Cepheids. As may be seen from Table III, I, the spectrum is rarely earlier than Class M, and very rarely later than Class M8; usually, though apparently not quite always, bright lines (hydrogen the most conspicuous) are displayed at some part of the cycle*. The behavior of the bright lines is typical, and very different from that displayed, for instance, by the very few Cepheids that have bright lines in their spectra. The behavior of five of the most conpicuous is shown by Merrill[58]; the appearance of hydrogen lines just after minimum, and their rise to maximum, first for Hδ, then for Hγ, are quite typical, and make it possible to estimate from an inspection of its spectrum the phase at which a long period variable was photographed. The successive appearance and rise to maximum of the two low-level FeI lines 4202 and 4308, and of the low-level line 4571 of MgI are equally characteristic.

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[55] P. A. S. P., 42, 287, 1930; Mt. W. Contr. 525, 1935.

[56] P. A. S. P., 42, 287, 1930; Mt. W. Contr. 525, 1935.

[57] Townley, Cannon, and Campbell, H. A., 79, No. 3, Supplementary Table, 1928.

The relative intensities of the lines of the Balmer series, Hβ being very weak, and especially Hε being absent at most phases, throw light on the level at which the bright lines are formed; evidently both the H and K lines and the titanium oxide bands are at higher levels than the hydrogen. It has been shown by Shajn[59] that all the apparent abnormalities in the intensities of the bright hydrogen lines can be interpreted in terms of overlying absorption.

The variations of the bright lines, taken in conjunction with the other spectral changes, constitute a puzzle that is still unsolved. Merrill,[60] in his paper concerning "Theories of Long Period Variable Stars", points out that the photosphere is not hot enough to supply the excitation required for the bright lines, and suggests that the spectral phenomena are able, because of the extreme depth and tenuity of the atmosphere, to proceed in partial independence of each other. As he shows in another paper,[61] the absorption spectrum is consistent with a temperature of about 2200°, but this temperature may not be the controlling factor in the appearance of the bright lines. Moreover, large changes in light may accompany very small changes in the absorption spectrum.[62] His parallel with the phenomena of the sunspot cycle (where the different parts of the surface are at different stages of the cycle, high latitudes showing the remains of an old cycle at the same time that low latitudes show evidences of the beginning of a new cycle), though not exact in detail, is very much to the point. Concerning the N and R stars of long period, which are certainly related, as the radial velocity data indicate, to the Me stars, Sanford makes the illuminating remark[63]: "There seems to be good evidence . . . that the emission lines are associated with the light maximum mechanism, and that they are not present during the one-third of the period which is symmetrical about light minimum". Thackeray's[64] suggestion that the second of the two ultimate lines of indium (4511) appears in the spectra of the late type variables, because the other almost coincides with Hδ, should be noted here.

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* Bright lines seem to be weaker in the earlier subdivisions of Class M (Merrill and Joy, Mt. W. Contr. 382, 1929). Although their occurrence in the long-period variables of Class N was long problematical, bright lines were definitely found by Sanford (P. A. S. P., 42, 287, 1930) in a number of the stars he examined, and he states that other stars, for which he did not note the bright lines at Mount Wilson, had been shown to have such at the Lick Observatory by Shane (L. O. B., 10, 79, 1920). Probably the occurrence of bright lines, perhaps very weak, must be regarded as characteristic.

[58] Mt. W. Contr. 471, 1933; *ibid.* 539, 1936.

[59] Zs. f. Ap., 10, 73, 1935.

[60] P. A., 43, 214, 1935.

A detailed list of the lines, dark and bright, that have been observed in the spectra of Me stars has been published by Merrill[65]; over half of the absorption lines are low-temperature lines of the metals. The more commonly observed bright lines are those of hydrogen, neutral iron, neutral magnesium, and neutral silicon. In addition, the forbidden lines of ionized iron are observed in the spectra of a few long-period variables[66], and "may frequently be present in the spectra of Me variables at minimum light . . . Not many . . . variables have been suitably observed".[67]

[61] Mt. W. Contr. 265, 1923.
[62] Mt. W. Contr. 539, 1936.
[63] P. A. S. P., 42, 287, 1930.
[64] Mt. W. Contr. 517, 1935.
[65] Mt. W. Contr. 265, 1923.
[66] Merrill and Burwell, Mt. W. Contr. 399, 1930.
[67] Merrill, Mt. W. Contr. 513, 21, 1935.

The spectral changes of o Ceti have been exhaustively discussed by Joy.[68] Among normal long-period variables the next most complete discussion is that of R Virginis by Merrill and Joy[69]. Details of the variability of the spectra of a dozen other long-period variables will be found in Merrill's later papers[70]; references are given in the notes to Table III, I.

In addition to the normal long-period variables of spectrum Me, two less normal stars have been especially discussed. The variable X Ophiuchi is atypical in that it is the second component of a double star, with separation $0''.22$. The other component (K0, $8^m.9$) is apparently non-variable, and as the range of the M6e star is from $6^m.8$ to $12^m.0$ the two spectra can be studied independently, the one at maximum, the other at minimum. The behavior of the variable is quite typical for its class, so that the estimate of its absolute magnitude (+0.3) on the basis of the spectroscopic absolute magnitude (+2.4) of the companion is of general significance.[71] It should be noted that the mass of the M6e component, deduced from the elements of the visual double, seems to be abnormally low when the absolute magnitude is considered.[72]

A far more abnormal long-period variable is R Aquarii, in whose spectrum are found the three components: a typical Me star; a nebular spectrum; and a (hypothetical) blue companion.[73] The latter is hypothetical so far as line spectrum is concerned, but undoubted evidences of an energy distribution appropriate to a hot star have been found in the changing light curve and color of the star during its abnormal light variations.[74]

The abnormality of R Aquarii is twofold: it shows evidence of a companion; and it is situated in a bright nebula, of which there is not only direct photographic evidence, but which also produces bright forbidden lines, unknown to unattended long-period variables, in the spectrum. As regards the first point: the existence of a companion is known for at least two other long-period variables (o Ceti, where also the companion is a variable Be star[75], and X Ophiuchi, noted above) and may not be uncommon[76]; a number of other red variable stars that appear to have high temperature companions is discussed in Chapter XI. As to the second point, for a variable star to be situated in a nebula is far from uncommon (see Chapter XI); but without a companion star of sufficient exciting power, such as R Aquarii possesses, the nebula might well remain invisible. Perhaps the forbidden lines of ionized iron, observed in the spectra of R Leonis, χ Cygni, and U Orionis,[77] may be signs of such a nebula. The portion of the R Aquarii spectrum that might relevantly be discussed in the present section is the first — that belonging to the red long-period variable; and so far as the published observations indicate, the behavior of this contributor is normal.

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[68] Mt. W. Contr. 311, 1926.

[69] Mt. W. Contr. 382, 1929.

[70] Merrill, Mt. W. Contr. 200, 1921; *ibid.* 264, 1923; P. A., 37, 44, 1929; Merrill and Burwell, Mt. W. Contr. 399, 1930; Merrill, *ibid.* 539, 1936.

[71] Merrill, Mt. W. Contr. 261, 1923.

[72] Merrill, P. A., 42, 190, 1934.

[73] Merrill, Mt. W. Contr. 206, 1921; *ibid.* 513, 1935.

[74] Unpublished, Harvard.

The occurrence of companions for several long-period variables has suggested that this phenomenon may be general; and attempts have been made to account for their bright-line spectra by excitation through a high-temperature companion. But Merrill finds that some long-period variables definitely show no sign in their spectra at minimum of the presence of a companion.[78]

ii. *Long-Period Variables with Spectra of Class S.*—Our knowledge of the long-period variables of Class Se is largely due to the work of Merrill[79], who has shown that they are spectroscopically closely related to the Me stars. All those that are sufficiently well observed are included in Table III, I, from which it can be seen that the radial velocity properties in particular are continuous with those of the Me stars. The spectral classifications are given in Tables III, I and III, IX; for the Se stars they are those provisionally suggested by Miss Davis[80]. From the entries in the table it is seen that periods

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[75] Joy, Mt. W. Contr. 311, 1926.
[76] See, however, below.
[77] Merrill and Burwell, Mt. W. Contr. 399, 1930.
[78] Mt. W. Contr. 539, 1936.
[79] Mt. W. Contr. 252, 1922; *ibid.* 306, 1926; Pop. Astr., 37, 444, 1929.
[80] P. A. S. P., 46, 267, 1934.

TABLE III, IX

LONG-PERIOD VARIABLES WITH SPECTRA OF CLASS S

Star	Designation	Period	Spectrum	Light Curve		
				a/b	c/d	e/f
		d				
R And	001838	409.2	S4e	4	6	
X And	001046	347.0	S2e	6	6	2.7:
W Aql	191007	493	Se	7	8	
TV Aur	045048	372	S	7	7	
UV Aur	051532	350	Se	7	7	
R Cam	142584	271	S4e	10	10	
T Cam	043065	373	S3e	10	14	1.7
V Cnc	081617	272	S2e	8	8	
R CMi	070310	338	S1e	10	11	
S Cas	011272†	612	S4e	7	7	1.9
U Cas	004047	278	S4e	8	9	
W Cas	004958	404	S1e	7	6	
SZ Cep	201276	327	Se	8:	9:	
W Cet	235715	351	Se*	12	12	1.6
U Cir	135866	145	S	11	10	
R Cyg	193449	425	S3e	6	7	
S Cyg	200357	324	S5e*	9	11	2.1
AA Cyg	200036	202	S*	8	8	
AD Cyg	202732a	365	S	8:	8:	
CN Cyg	201559	198	S	10:	10:	
CY Cyg	204345	..	S	9::	9::	
χ Cyg	194632	347	Se*	9	9	2.0
Z Del	202817	304	S5e	10	10	
R Gem	070122a	370	S3e	7	10	
T Gem	074323	287	S4e	8	14	
VX Gem	070714	377	Se	9	10	
RW Lib	151723	203	S5e	9:	9:	
S Lup	144646a	346	Se	10	8	2.3
R Lyn	065355	379	S3e	10	10	2.2
SU Mon	073710	..	S	8::	10::	
R Ori	045307	378	S1e	8	8	
T Sgr	191017	390	S4e	8	8	
S UMa	123961	225	S2e	10	13	

* Combine spectral characteristics of S and M (Merrill, P. A., *37*, 444, 1929).

† Light curve very variable.

for Se stars cover most of the range covered by Me stars, and that every type of light curve, except Campbell's type D, is indiscriminately represented. The only strong correlation shown by the S stars[81] is that of spectral class with the difference between absorption and emission velocities. The Se stars may be considered close relations of the Me stars, especially as a few stars show the Me and Se characteristics simultaneously or interchangeably[82]. These objects are of especial interest, and should be examined photometrically with particular care. The difference between the stars of Classes M and S lies in the difference in intensity of the absorption bands of titanium oxide and zirconium oxide; and that this relative intensity is governed by the atmospheric conditions is shown by the fact that some Me stars, notably χ Cygni, occasionally show the characteristics of Class Se. The difference in conditions for the production of the two types of spectrum has been examined by Richardson[83]. The presence of zirconium oxide in the spectra of some ("approximately") non-variable M stars (such as β Pegasi and ρ Persei) is discussed by Bobrovnikoff,[84] who attributes it to abnormal abundance of zirconium.

iii. *Long-Period Variables with Spectra of Class R.*—The spectral Class R, distinguished from the parallel Class K by the band spectra of carbon compounds, is of especial interest among the variable stars. There are but few variables of this spectral class, and almost all are either members of interesting groups of variables, or are peculiar members of the group to which they belong. *All* the variable stars that are at present known to have spectra of Class R are listed in Table III, X. Notes in the last column indicate the type of variable with which we are concerned, with references to other parts of the book for variables not treated in the present section.

We see from Table III, X that six long period variables (though of small range) are represented in a list containing eighteen actual Class R variables; of the remainder, four belong to the R Coronae Borealis type, and V Arietis and ST Scorpii are probably irregular. The three stars W Canis Minoris, TZ Carinae, and TV Velorum would repay further study; and RU Camelopardalis, one of the most puzzling stars known, is discussed in the next chapter.

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[81] Miss Davis, *op. cit.*

[82] Merrill, Pop. Astr., 37, 444, 1929; Mt. W. Contr. 539, 1936.

[83] Mt. W. Contr. 479, 1933.

[84] Ap. J., 79, 483, 1934.

TABLE III, X

VARIABLE STARS WITH SPECTRA OF CLASS R

Star	Designation	Mag.	A	Spectrum	Remarks
S Aps	1459*71*	10.0	5.2	R3	R Coronae Borealis class; see Chapter X.
N Aql 1919	191301	10.4	15.0	R0	A long-period variable, probably resembling W Orionis; see Chapter VII.
V Ari	020911	8.3	0.7	R8	
S Cam	053068	7.8	3.6	R8e	Long-period variable; P = 328^d.
RU Cam	071069	7.8	1.2	R0e–K0	Probably an abnormal Cepheid.
W CMi	074305	10.3	1.0	R8	
TZ Car	1042*65*	8.4	0.8	R	
Z Cen	1334*31*	8.0	8.2	(R)	A nova; spectrum should be Q; see Chapter VIII.
V CrA	1840*38*	9.0	1.0	R0	R Coronae Borealis star; see Chapter X.
W CrA	1758*39*	10.0	1.0	R5	Long-period variable; P=109^d (Harvard, unpublished).
WX CrA	1802*37*	12.2	4.0	R5	R Coronae Borealis star; see Chapter X.
VX Cyg	205339	9.7	1.1	(Rp)	A Cepheid.
VX Gem	070714	10.8	14.9	Rpe	Long-period variable; P =377^d. Note that Sanford (Ap. J., 82, 208, 1935) calls the star V Geminorum (see G. u. L., II, 2, III, 1936).
TX Lac	224154	11.5	0.6	R	Long-period variable? P=240^d?
ST Sco	1630*31*	7.8	1.9	R5	
RS Tel	1811*46*	9.3	3.7	R8	R Coronae Borealis star; see Chapter X.
TV Vel	1030*53*	11.0	4.0	R8	
RU Vir	124204	8.0	3.6	R3ep	Long-period variable; P =439^d.

Concerning the six long-period variables there is nothing very unusual, except with regard to the so-called Nova Aquilae No. 4, which is considered by Graff[85] to be a long-period variable. An excellent spectrum taken at Lick Observatory by Lundmark[86] is of unmistakable R class, and when observa-

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[85] B. Z., 5, 41, 29, 1932.

[86] P. A. S. P., 33, pp. 314-316, 1921.

TABLE III, XI

LONG-PERIOD VARIABLES WITH SPECTRA OF CLASS N

Star	Designation	Mag.	A	Spectrum	Period
ST And	233335	8.3	4.1	N3e	338^d
VY And	001444	9.5	1.5	Nb	149
AQ And	002235	6.9	1.3	Nb	332
S Aur	052034	8.3	3.7	N3	591
V Aur	061647	8.3	4.5	N3e	357
TX Aur	050238	8.5	0.7	N3	330
UW Aur	065041	9.6	3.0	N3	530
AZ Aur	055439	10.5	5.0	N0e	416
U Cam	033362	7.6	1.2	N5	419
T Cnc	085120	8.0	2.0	N3	500
X Cas	014958	8.4	4.7	Nie	425
S Cep	213678	7.0	5.9	N8e	482
V CrB	154639	6.9	5.5	N3e	365
V Cru	125057	10.4	3.0	Ne	377
Z Cru	120663	10.8	2.7	N0	341
U Cyg	201647	6.1	5.7	Npe	456
V Cyg	203847	6.8	7.0	Npe	416
WX Cyg	205030	8.7	4.0	N3e	410
YY Cyg	211841	8.5	1.0	Nc	387
T Dra	175458	7.5	6.5	N0e	425
V Hya*	104620	6.0	6.5	N6	527
RY Hya	081403	8.3	3.0	Nbe	535
R Lep	154736	6.0	4.4	N6e	440
T Lyn	081633	8.0	4.0	N0e	419
U Lyr	191637	8.3	3.7	N0e	460
V Oph	162112	6.9	3.9	N3e	301
W Ori†	050001	5.9	1.8	N5	200
RX Peg	215122	7.7	0.9	N3	175
RZ Peg	220133	8.1	5.1	Ne	440
Y Per	032043	8.2	2.6	N3e	254
SY Per	040950	9.5	3.0	N3	476
SX Sco	174035	9.6	1.5	Nb	128:
TT Tau	044528	8.1	0.7	N3	166
SS Vir	122001	7.2	1.6	Np	354
BD Vul	203326	12	3	N	448

* Large variation in mean brightness.

† Large variation in mean brightness, accompanied by marked spectral changes (unpublished Harvard observations by Mrs. C. Anger Rieke).

tions of the light variation are assembled the star is seen to be probably a variable of similar type to V Hydrae and W Orionis, discussed in the section that follows. All the long-

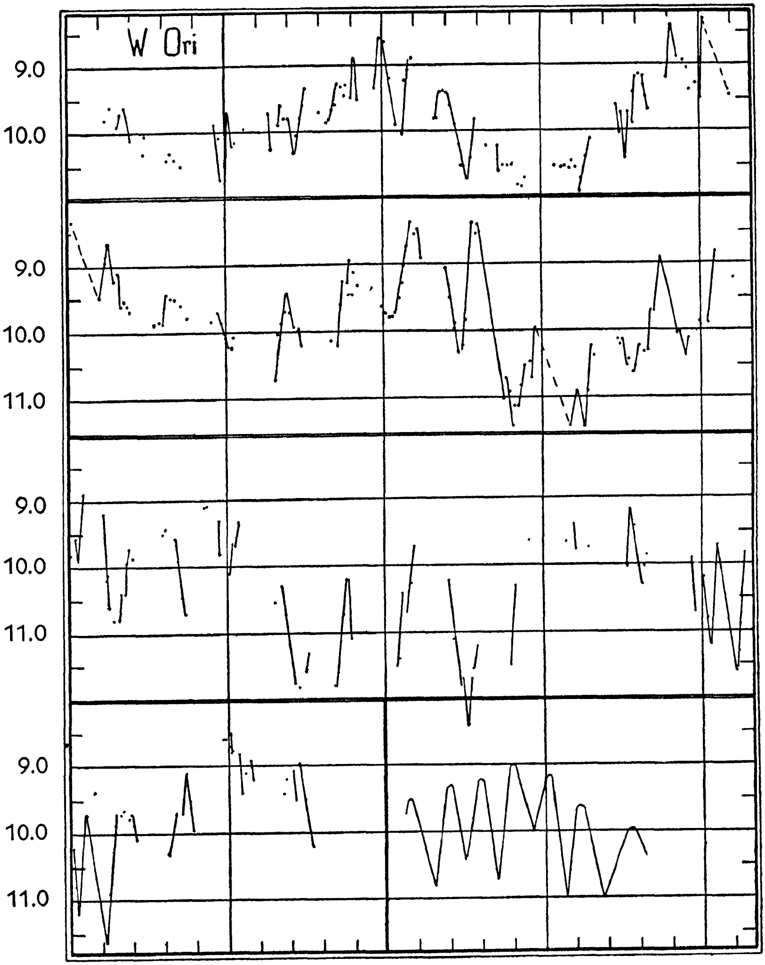

Figure III, 5.—Variations of W Orionis. The observations are photographic estimates made on Harvard plates. Abscissae are Julian Days (short vertical lines indicate intervals of 200 days, vertical cross-lines, intervals of 1000 days). The observations cover the interval from J.D. 2414000 to J.D. 2428000. In the lower right corner is the mean light curve for the whole interval, showing the long-term variation (short vertical lines indicate intervals of 2000 days, vertical cross-lines, intervals of 10,000 days). Ordinates are photographic magnitudes, as indicated in the margin.

period variables of Class R may be treated as a subdivision of the long-period variables of Class N, to which the next section is devoted.

iv. *Long-Period Variables with Spectra of Class N.*—The spectra of Class N show, with greater intensity, the bands of carbon compounds that characterize Class R. The majority of the N stars are variable, but, because they are extremely red, the observations are difficult, and probably more regularities are present than have actually been noted. Most of those in Prager's catalogue are given as irregular, or of unknown type, and there is little point in reproducing the entire list. Accordingly, Table III, XI contains only long-period variables of Class N with well determined periods; it will be noted that the average period is greater, and the range smaller, than those of the Me and Se stars. It is noteworthy that no R Coronae Borealis stars are given as of Class N, although so many of them are of Class R and the corresponding[87] (hotter) Class (G prime). The variations of the N stars are uniformly more irregular, and more subject to small sudden fluctuations, than those of the stars of any other spectral class.[88]

In addition to the above list, the stars TT Cygni and X Sagittae are noted as semi-regular; both should be interesting, if difficult, subjects for photometric study; very likely stars of this group that are apparently semi-regular partake of the peculiarities shown by V Hydrae and W Orionis.

TABLE III, XII

LONG PERIOD VARIABLES WITH SPECTRA CLASSED "PECULIAR"

Star	Designation	Mag.	A	Period	Notes
VX And	001444	10.7	1.1	Irr.	
RZ Cyg	204846	9.6	4.0	546	Light curve is uncommon: $a/b = 33$, $c/d = 10.0$, and $e/f = 3.0$.
SY Mus	112*764*	*11.3*	*0.9*	625	Light curve, Uitterdijk, B. A. N. 256, 1934; N. K. Greenstein, H. B. 906, 6, 1937.
RZ Sgr	2008*44*	8.0	2.2	212	

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[87] C. Payne Gaposchkin, H. B. 903, 35, 1936.

[88] See for instance, ten Bruggencate, Bosscha Ann., 2C, 25, 1928.

Before leaving the list of stars with spectra of Class N, we must mention a small group of stars whose spectra are designated "peculiar". All except SY Muscae are evidently very red variables closely affiliated with the preceding. A list of such stars is given in Table III, XII. They should not be confused with other stars that have totally different "peculiar spectra", like CI Cygni[89], GG Carinae[90], Z Canis Majoris[91], and β Cephei.[92]

31. Light Curves of Individual Stars.—By far the most extensive data concerning the light curves of long-period variables involve visual light curves. Between four and five hundred stars, regularly observed by the A. A. V. S. O. for example, have been used to form the collection of the light curves of long-period variables now at the Harvard Observatory. The recorder is Mr. Campbell. A comparable collection of visual light curves has been formed by the British Astronomical Association, and a number of the curves for individual maxima have been published in the Memoirs of the Association.[93]

The information conveyed by the light curve is contained in Table III, I, for a considerable number of well-observed stars. The amplitudes are on the average between four and five magnitudes. The table can, however, give no indication of changes in the form of successive maxima of the same star, nor of departures from regularity in the time of returning to maximum. All long-period variables are subject to departures from strict punctuality in attaining maximum (and minimum) and the light curve is never repeated precisely in successive maxima. Sometimes this lack of precise repetition appears in great differences in the magnitude attained at maximum, which may amount, as in the light curve of χ Cygni, to more than three magnitudes.[94] The tendency appears, with greater or less conspicuousness, for the light curves of all long-period variables, and is distributed more or less at random, at least for stars with periods greater than a hundred days.

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[89] See Table XI, II.

[90] See Table XI, I.

[91] See Table XI, II.

[92] Section 34.

[93] Mem. B. A. A., Appendices to Vols. 22, 25, 1924; Vols. 15, 18, 1913.

[94] L. Campbell, unpublished discussion.

A second type of variability of light curve concerns the humps that occur for many long-period variables (χ Cygni is again a notable example; almost every cycle is marked by a hump at some point on the rising branch of the light curve, never twice at the same level or of the same intensity). For the other stars the hump is so pronounced as to produce a secondary minimum. This has led to the invention of a class with a hump or with a secondary maximum. From our Table III, I, one sees the advantage of numerical parameters, for they give not only an indication of the existence of a hump, but also its accurate position. The star UZ Circini[95] is a striking example of variability of depth and position of a secondary minimum in different cycles. In the light curve of U Persei the changes are even more conspicuous[96]: in some cycles the secondary minimum is strongly marked; at others the maximum is continuously rounded, showing no tendency to a central depression. It should be emphasized that these are typical cases, not isolated examples, of the manner in which the light curves of almost all long-period variables alter from one maximum to another.

Some light curves are indeed so variable as to defy classification. Ludendorff assigns several classes to the light curves of a number of stars given in Table III, I. He notes variability, for example, for the stars R Aquarii, R Bootis, Z Cygni, R Pictoris, Z Scorpii, and R Volantis.

What has been said above applies to stars with periods greater than a hundred days. Those with periods between fifty and a hundred days show the same type of variability of light curve, but often to a more pronounced degree. Although several of these stars are actually to be accounted long-period variables, their behavior will be treated in the chapter (Chapter V) that is devoted to the stars closely related to the Great Sequence.

The variability in the form of the light curve has a parallel in the variability in the length of the cycle from one maximum

[95] Swope, H. B. 883, 1931.
[96] O'Connell, H. B. 892, 1933.

to the next. No two cycles for any one variable star are precisely alike, and the observed maxima of even the best-known long-period variables deviate, on the average, about ten days from those predicted on the basis of a constant period. Much study has been devoted in the past to the problem of detecting secular or periodic changes in the length of the cycle. Although not long since it was held that the periods of a large number of long-period variables were probably changing (either in a steady, or an irregular, or a periodic manner), it has been concluded by Sterne and Campbell[97] on the basis of a recent study that there are but few stars that show definite evidences of real changes* in period. The two most conspicuous examples are the stars R Hydrae and R Aquilae, both of which are almost certainly changing in period.

An unpublished series of photographic light curves, derived by one of the writers from Harvard plate material, was used as the basis of the measured properties given in Table III, I for a number of stars. The photographic light curves seem to be precisely similar to the visual light curves, not only in general but in detail, displaying all the peculiarities of form and duplicating the humps and secondary minima. This is an important observation, since it shows that, for two effective wave-lengths about a thousand Angstroms apart, the small changes of brightness run parallel, so that they probably represent changes in the total light of the star, not fluctuations produced by spectral changes, and affecting only limited ranges of wave-length. This point is further strengthened by the observed infra-red light changes, established by Hetzler at Yerkes.

An important piece of information that can be derived from a careful comparison of visual and photographic light curves concerns the changes of color as the star goes from maximum to minimum. The extensive work of comparing the visual and photographic brightness at individual minima (far superior to a comparison of mean light curves for this purpose) was carried out by Gerasimovič and Shapley[98], with the important result for the Me stars that they are not very different in color at maximum and at minimum, with perhaps a slight tendency to be bluer at minimum. This phenomenon has long been understood in terms of the increasing absorption by titanium oxide in the red, which counteracts the relative decrease of intensity in the blue, as the effective temperature falls at minimum[99]. The parallelism of visual and photographic light curves for Me stars does not, however, follow for N stars, where the band absorption at minimum cuts down the blue end of the spectrum, thus working with, and not against, the change of relative energy as the temperature falls towards minimum. The visual and photographic light curves of RV Centauri, discussed by Campbell and Hoffleit[100], brought this out very clearly. There seem to be few data concerning the changes in apparent color for R and S stars.

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[97] H. A., 105, No. 24, 1936.

* Change of period is here to be understood in a statistical sense.

[98] H. B. 872, 1929.

Infra-red light curves (effective wave-length 8500 A) have recently been published by Hetzler for a number of long-period variables, and such light curves are second only to radiometric light curves in importance in giving an idea of the true changes of brightness of the long-period variables[101]. It is noteworthy that for the three stars T Cephei, χ Cygni, and R Cassiopeiae, the infra-red light curve duplicates the form of the visual light curve, which is additional and very strong evidence that the peculiarities of the curves are part of the true light variation, and not accidental circumstances affecting only a small part of the energy range.

From all absolute standpoints the light curves that have the most significance for long-period variables are the radiometric light curves. The results of Pettit and Nicholson's studies[102] of long-period variables by this means are summarized in Table III, XIII. The chief points for our purpose are the smallness of the range—averaging less than a magnitude—and the temperatures tabulated in the last column. It should be mentioned that Wurm[103] has derived considerably lower

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[99] For a general discussion, see Payne, *The Stars of High Luminosity*, where references are given to earlier investigations.

[100] H. B. 875, 1930.

[101] Ap. J., 83, 372, 1936.

[102] Mt. W. Contr. 369, 1927.

[103] Zs. F. Ap., 5, 260, 1932.

(excitation) temperatures from a study of the intensities of carbon and cyanogen bands, giving 1500° for Class N0. He considers that the temperatures of N stars vary only over a hundred degrees. Excitation temperatures may well be lower than color or radiation temperatures, as has been found for the sun by R. B. King.[104]

Table III, XIII

Star	Spectrum	Visual		Radiometric		Heat Index		Temperature	
		M	A	M	A	Max.	Min.	Max.	Min.
VX And	N7	8.8	..	4.2	..	4.6	..	2010	..
R Aqr	M6e+P	6.0	6.8	1.9	0.7	4.1	10.2	2180	1760
R Aql	M5e—8e	6.1	5.5	1.8	0.9	4.3	8.9	2360	1890
R Cnc	M6e—8e	6.6	4.8	1.9	0.9	4.7	8.6	2450	1890
X Cnc	N3	6.4	..	3.2	..	3.2	..	2260	..
o Cet	M5e—8	3.6	5.8	—0.2	0.9	3.8	8.6	2540	2020
χ Cyg	M6e—8e	5.2	8.1	0.4	1.2	4.8	11.7	2260	1580
R Hya	M6e—9e	4.2	5.1	0.0	1.0	4.2	8.3	2360	1950
U Hya	N2	5.4	..	2.2	..	3.2	..	2360	..
R Leo	M6e—9e	5.9	4.3	0.1	0.8	5.8	9.3	2260	1760
R LMi	M7e—8e	7.0	5.4	2.1	0.9	4.9	9.4	2260	1830
X Oph	M5e—7e	6.6	4.4	1.6	0.7	5.0	8.7	2260	1890
R Tri	M4e—8e	6.3	5.7	3.4	0.7	2.9	7.7	..	1950

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[104] Ap. J., 87, 40, 1938.

TABLE III, I

SELECTED LIST OF LONG PERIOD VARIABLES

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
R And	001838	86	—24	6.9	6.4	409.2	S4e	— 8.2	— 36.3	Cb	α_3	4	6		R
T And	001726	84	—35	8.5	5.3	281.0	M3e	— 90	— 94.8	Cb	β_1	10	10		
U And	010940	96	—22	9.9	4.1	345.7	M6e			Cb	α_2	7	7		
V And	004435	91	—27	9.2	4.4	258	M2e–3e	(+ 16.1)	+ 8.0	Bb	β	9	9		
W And	021143a	107	—15	7.3	6.4	397	M7e–8e	— 28.5	— 44.6	Cd	α_5–γ_1	6	6	2.7:	
X And	001046	85	—15	9.0	5.8	347.0	S2e	(+ 1)	— 18.2	Bb	α_3	6	7		
Y And	013338	101	—22	9.4	4.7	220.2	M3e–4e	(— 3.8)	— 16.8	Cb	α_4	9	9		
RR And	004533	92	—28	9.2	5.8	330	M4e–5e			B	β_1	9	9		
RW And	004132	91	—30	8.8	5.8	430	M8e			Cb	α_2	8	8		
SV And	235939	82	—22	8.6	4.9	315.3	M7e	(— 89.1)	— 98.8	Cb	α_3	8	7		
UZ And	011041	96	—20	10.1	4.4	313	M7e			Cb	α_2	7	6		
T Aps	134677	274	—16	8.4	5.6	261	M3e			Bb	α_4	9:	9:		
R Aqr	233815	38	—72	6.4	3.9	386.8	M6e+P	— 19	— 33	Cb	α_1	7	4		R
S Aqr	225120	10	—64	8.2	5.8	280.0	M4e	(— 57.9)	— 66.4	Bb	α_4?	6	6		
T Aqr	204405	10	—30	7.6	5.3	202.5	M2e–5e	— 38.2	— 54.9	Aa	β_2	9	9		
V Aqr	204102	18	—25	8.3	1.9	245.5	M6e	(— 43.4)	— 52.9	Ba	Pec.	7:	7:		
W Aqr	204104	11	—29	8.4	5.6	383.1	Me			C	α_3	8	7		
RR Aqr	210903	17	—34	9.2	4.8	182	M2e–3e	(—182)	—191.0	Bb	α_4	8	10		
RT Aqr	221722	1	—57	8.7	4.4	246	M5e–6e	(— 33)	— 43		β	8	9		
R Aql	190108	10	0	6.0	5.4	329.3	M5e–8e	+ 31.5	— 19.4	Cb	α_4	8	7		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	Numerical Parameters of Light Curve 10 c/d	e/f	Rem.
		°	°		*m*	*d*									
X Aql	194604	12	−12	8.8	6.0	347	M5e			Cb	α_3–γ_1	9	6		
W Aql	191007	357	−10	8.4	5.6	493	Se			Cb		7	8		
Z Aql	200906	5	−23	9.1	4.4	128.6	M3e	(− 7.9)	− 10.3	Bb	α_4	10	10		
RR Aql	195202	6	−16	8.9	4.6	395	M6e–7e			Cb	α_2	2	10		
RT Aql	193311	16	− 6	8.0	5.8	326	M6e–8e	(− 42.0)	− 54.2	Cb	α_3	8	8		
RU Aql	200812	22	−13	9.3	4.5	273.0	M4e			Ca	α_3	9	8		
RV Aql	193509	15	− 8	9.1	5.2	219.4	M3e			Cb	α_4	9	10		
SY Aql	200212	22	−12	9.5	4.9	357	M7e			Cb	α_2	9	7		
U Ara	174551	309	−13	8.5	4.7	224.5	M3e–5e			Bc	α_3	10	9		
R Ari	021024	114	−33	8.2	5.9	186.5	M3e	+114.4	+102.0	Aa	β_3	10	12		
U Ari	030514	134	−35	8.2	6.4	372	M4e–6e			Cc	α_3	7	10		
R Aur	050953	124	+10	8.0	5.1	457	M7e–8e	(+ 8)	− 13	Bd	γ_1	10	10	1.8	
S Aur	052034	141	+ 1	8.8	1.9	578	N3			Ab	β_4	9	10		
U Aur	053531	145	+ 3	8.6	5.4	410	M7e			Cd	α_1	4:	14:		
V Aur	061647	134	+17	9.1	2.8	352	N3e			Bc	β_2	11	10		
W Aur	052036	139	+ 3	9.2	4.5	275	M3e			Bb	α_3	8	10		
X Aur	060450	131	+16	8.3	4.6	163.5	M2e–4e	(− 20.2)	− 26.2	Ac	β_3	10	11		
UX Aur	050849	127	+ 8	8.1	0.6	102.7	M2			. .	α_3?	8	9		
R Boo	143227	5	+65	7.1	5.2	223.2	M3e–5e	− 46	− 57	Ba	β	10	10		R
S Boo	141954	63	+58	8.5	4.9	270.8	M3e–5e	(− 17.0)	− 25.0	Ba	β_2	9	9		

TABLE III, I—*Continued*

								Rad. Vel.		Light Curve		Numerical Parameters of Light Curve			
Star	Des.	l	b	M	A	Period	Spectrum	Abs. km/sec	Em. km/sec	C*	L†	10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
V Boo	142539a	34	+65	7.5	3.2	259.5	M6e	− 31	− 42	Aa	α pec.	10	11		
Z Boo	140113	328	+66	9.3	5.1	282	M4e			Bb	α_3	7	7		
R Cae	043738	208	−40	8.3	4.7	394	M6e			Cb	α_3	8	7		
R Cam	142584	86	+33	8.3	4.8	271.2	S4e	(− 32)	− 42.9	Ab	β_3	10	10		
S Cam	053068	112	+20	8.3	2.3	328	R8			Ad	β_3–β_4	11	15	2.2	
T Cam	043065	111	+13	8.1	5.6	373	S3e	(+ 3)	− 19	Ad	$\gamma_1(\beta_3)$	10	14	1.7	
V Cam	054974	107	+23	9.6	3.9	513	M7e			Cb	α_1	5	5	0.6	
X Cam	043274	104	+20	8.2	4.6	142.3	M3e	− 2.3	− 5.8	Aa	β_3	10	11		
R Cnc	081112	180	+25	6.8	4.4	360	M6e–8e	+ 32.1	− 18.4	Cb	α_4–γ_1	9	5		
U Cnc	083019	174	+33	9.4	4.4	304.5	M2e	(+ 71)	+ 61	Cb	α_1	8	4		
V Cnc	081617	175	+30	7.7	5.0	272.4	S2e	(− 2)	− 13.5	Aa	α_4	8	8		
W Cnc	090425	170	+42	8.2	5.9	392	M7e	(+ 51.3)	+ 34.7	Cb	α_3	5	8		
R CVn	134440	45	+73	7.6	4.3	325.3	M6e–8e	− 8.9	− 23.6	Ba	α_4	10	10		
T CVn	122532	125	+85	9.3	3.0	290	M5			Aa	β_3	9	10		
U CVn	124238	87	+79	*8.0*	]*4.5*	340	M7e	(− 27)	− 43.7	..		7	9		
V CVn	131546	70	+71	6.8	1.1	192	M5e			Aa	α pec.	9:	10:		
R CMi	070310	173	+10	7.9	2.7	338	S1e	(+ 51)	+ 33.3	Ab	β_3	10	11		
S CMi	072708	178	+14	7.5	5.2	332	M6e–8	(+ 67.2)	+ 54.6	Bd	β_1–γ_1	10	10	2.3	
U CMi	073508	178	+17	8.8	4.2	410.4	M4e			Ad	γ_1	13	20	1.7	
T Cap	211615	4	−42	9.6	4.0	269.2	M2e–3e			Cb	α_3	11	11	1.8	

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
V Cap	210124	351	—41	9.0	)4.5	275.6	M3e–5e			Cb	α_3	9	7		
R Car	092962	250	— 8	4.4	5.0	308	M4e–7			Ca	β_1–γ_1	10	14	2.5	
S Car	100661	253	— 4	5.3	4.0	149.4	K7e–M4			Ad	β_3–γ_1	10	13	2.0	
RW Car	091868	253	—13	9.0	5.0	322	M4e			Ca	α_4	8	7	3.0	
RZ Car	103270	260	—11	10.1	5.3	272	M4e			Cb	α_2	6	6		
R Cas	235350	83	—11	7.1	5.8	431.4	M6e–8e	+ 30	+ 8.2	Cb	α_4–γ_1	6	8	..	R
S Cas	011272	93	+10	8.3	6.2	612.5	S4e	(20.±)	— 54	Cd	Pec.	7	7	1.9	
T Cas	001755	87	— 7	8.2	3.7	443	M6e–8e	— 11.0	— 24.8	Ad	γ_1	13	14	2.0	R
U Cas	004047	90	—16	8.4	6.1	277.6	S4e	— 45	— 56.6	Bb	α_4–β	8	9	..	
V Cas	230759	78	—11	7.8	4.6	228.8	M5e–7e	— 30.5	— 47.6	Ba	β_2	10	10	..	
W Cas	004958	91	— 4	8.8	2.2	400.4	S1e			Aa	β_3	7	6		
X Cas	014958	95	— 4	8.4	4.7	425.4	N1eα			Ca		6	6		
Y Cas	235855	84	— 6	9.7	4.4	415.4	M6e–8			Cb	α_3	8	6	2.5	
RR Cas	235053	82	— 9	9.6	4.1	307.7	——			Ac		11	11	1.8	
R Cen	140959	282	+ 1	6.0	5.0	564.3	M4e–5e			D	γ_2	40	30	2.5	
T Cen	133633	283	+27	6.1	1.6	90.8	K8e–M3	+ 24	+ 21	Aa	β_3	9	10		
U Cen	122854	268	+ 8	8.2	5.2	220.3	M3e–4e			Ba	β_2	10	9		
W Cen	115058	263	+ 3	8.3	4.8	202.2	M3e–4e			Cb	β_1	9	9		
X Cen	114441	260	+20	7.4	6.2	314.3	M5e–6e			Cb	α_3	7	8		
RS Cen	111661	260	— 1	8.8	4.3	164.5	M3e–4e			Ab	β_2	10	14		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
RT Cen	134236	284	+24	7.9	4.7	253.3	——			Ab		10	11		
RV Cen	133155	277	+ 5	7.0	2.5	460	N3			Ad		5	5		
RX Cen	134536	284	+24	8.6	6.2	328.6	——			Cb		6	5		
UY Cen	131044	275	+18	7.1	1.0	186	K5p					10	12		
S Cep	213678	81	+19	8.1	3.2	485.8	N8eα			Ad	β_5—β_4	12	12	2.7	
T Cep	210868	72	+13	6.1	4.0	387	M5e–7e	— 10.7	— 26.1	Cb	γ_1	10	10	1.8	R
X Cep	210382	83	+22	9.5	)5.5	534	M7e			Cb	α_1	4	4		
Y Cep	003179	89	+18	9.5	5.4	330	M5e–6e			Cb	α_3	8	8		
o Cet	021403	136	—57	3.4	5.8	331.6	M5e–8	+ 64.3	+ 48.1	Cb	α_3	7	7		R
R Cet	022000	135	—53	8.1	4.8	166.6	M4e	+ 42.5	+ 31.6	Ab	α_4	9	10		
S Cet	001909	74	—71	8.2	5.7	320.2	M3e–4e	+ 32	+ 20	Bd	β	9	10	2.0	
U Cet	022813	156	—61	7.5	4.9	233	M2e–4e	— 27	— 39.4	Ab	α_4	9	10		
V Cet	235209	59	—68	9.1	5.2	260	M3e	(+ 51.1)	+ 43.1	Cd	α_3	9	9		
W Cet	235715	51	—74	7.4	7.1	351.2	Sep			Ac	α_4	12	12	1.6	
X Cet	031401	151	—44	8.8	3.7	175.7	M2e			Aa	β_3	10	10		
Z Cet	010102	102	—63	8.8	4.3	183.7	M1e–4e			Ca	β	10	12	2.0:	
R Cha	082476	256	—21	8.4	5.4	335	M6e			Cb	α_3	7	9		
R Col	054629	202	—24	9.1	5.2	324	M3e–4e			Cb	α_3	7	6		
T Col	051533	204	—32	7.5	4.6	225	M3e–6	(+ 66.4)	+ 53.4	Ba	β_2	8	9		
R Com	115919	221	+77	8.4	5.6	363.0	M5e	(— 7.0)	— 22.0	Cb	α_2	6	7		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	Numerical Parameters of Light Curve 10 c/d	Numerical Parameters of Light Curve e/f	Rem.
		°	°		*m*	*d*									
S CrB	151731	16	+56	7.0	5.8	361.2	M6e–8e	− 1.0	− 22	Cb	α_3	7	9		
W CrB	161138	27	+45	8.3	4.7	238.4	M2e–4e	(+ 20.1)	+ 10.5	Ca	α_4–γ_1	10	9	3.0	
X CrB	154536	24	+51	9.0	4.6	238.2	M5e–7e			Ca	β_1	10	9		
Z CrB	155229	14	+48	10.0	4.1	250	M4e			Bb	α_4	8	10		
R Crv	121418	262	+43	7.4	5.6	317.4	M5e–7e	(− 22)	− 34	Ba	β_1	8	10		
χ Cyg	194632	36	+ 3	5.1	8.2	406.6	M6e–8e, S5e	− 0.5	− 19.7	Bd	α_4–γ_1	9	9	2.0	R
R Cyg	193449	50	+13	7.4	6.5	425.5	S3e	(− 15)	− 45.0	Cb		6	7	2.0	R
S Cyg	200357	59	+13	10	6	324	S5e	(− 21.7)	− 33.7	Cc	Pec.	8	7		
U Cyg	201647	52	+ 6	7.0	3.6	464	R8eα			Ba		9	11	2.1	
V Cyg	203847	54	+ 3	6.8	7.0	415.5	Npe			Ba		6	7		
W Cyg	213244	59	− 5	5.4	1.6	129.6	M5	− 27	− 26	Bc?	γ_2	5	4	3.0	
Z Cyg	195849	52	+ 9	8.8	4.5	262.4	M5e	(−165.1)	−173.1	Cb	α_2	10	9		
RS Cyg	200938	44	+ 2	7.2	1.7	413	N3eα			D		25	20	2.5	
RT Cyg	194048	49	+11	7.3	4.5	190.4	M2e–4e	(−115.0)	−125.5	Aa	β_3	10	9		
RU Cyg	213753	65	+ 1	7.5	2.8	461	M8e			D	Pec.	10	10		
RZ Cyg	204846	55	+ 1	9.6	4.0	546	Pec.			D		33	10	3.0	
ST Cyg	205954	59	+ 8	9.8	4.1	333.5	M6e			Cb	β_2	11	11	2.0	
SX Cyg	201130	38	− 3	8.8	5.2	412.0	M7e			Cb	α_1	7	5		
TU Cyg	194348	50	+11	9.5	4.5	219.2	M3e			Bb	α_4	10	9		
TY Cyg	192928	30	+ 3	9.4	4.3	349	M8			Bd		9	9	2.5	

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	Numerical Parameters of Light Curve 10 c/d	Numerical Parameters of Light Curve e/f	Rem.
		°	°		*m*	*d*									
UX Cyg	205030a	43	−10	7.4	)5.6	560	M4e–5e				α_1	5	5		
AA Cyg	200036	41	+ 3	8.4	0.8	202	S4					8	8		
R Del	201008	19	−15	8.4	5.0	284.0	M5e–6e	(− 46.1)	− 54.8	Cb	α_4	10	9		
T Del	204016	30	−17	9.4	5.4	332.2	M3e–6e			Cb	α_4	7	7		
V Del	204318	32	−16	9.9	6.1	533.3	M4e			Cb	α_1	6	4		
X Del	205017	32	−19	8.9	5.0	280.7	M4e	− 56.2	− 62.9	Cb	α_3	7	6		
Z Del	202817	29	−14	9.0	4.9	304.1	S5e			Ba		10	10		
R Dra	163266	65	+38	7.6	4.7	245.5	M5e–7e	−138	−144.2	Bb	α_4	9	9	2.0:	
T Dra	175458a	54	+29	7.5	6.4	425.0	N0e			Ba		6	7		
U Dra	190967	65	+23	9.5	4.3	312.7	M6e–8			Cd	β_1	10	9	2.5	
V Dra	175654	50	+29	9.3	5.3	277.1	Me			Bb	β_1	10	10		
W Dra	180565	63	+29	9.6	4.5	275.5	M3e–4e			Ab	α_4	9	10		
R Equ	210812	31	−25	9.1	5.1	262	M3e–4e	(− 54.0)	− 62.0	Cb	α_4	8	9		
T Eri	035124	186	−47	8.3	4.2	251.5	M3e–5e	(+ 43)	+ 34	Cc	α_4	9	8		
W Eri	040725	189	−44	8.7	4.6	374	Me	(+ 27.1)	+ 14.4	Cb	α_2	7	8		
R Gem	070122a	162	+15	7.1	6.1	370	S3e	− 36	− 57.4	Bb		7	10		R
S Gem	073723	165	+23	8.8	5.2	293.4	M4e			Cb	α_3	5	5		
T Gem	074323	165	+25	8.7	5.0	287	S4e	(+ 25)	+ 11.8	Aa		8	14		
V Gem	071713	172	+14	8.3	6.0	275.8	M4e–5e	+ 22	+ 10.6	Bb	α_4	9	9		
X Gem	060430	153	+14	8.2	5.0	263.5	M5e	(+ 75.2)	+ 67.2	Ba	β_1	9	10		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
R Gru	214247	318	−51	8.4	5.5	330.9	M5e			Bb	α_3	7	8		
S Gru	221948	313	−56	7.6	5.8	401.8	M5e–7e			Cb	α_4–γ_1	8	9:		
T Gru	221938	332	−59	8.6	3.0	137.2	M0e			Aa	β_3	9	11		
R Her	160118	0	+44	8.9	5.5	318.4	M6e	(− 30.6)	− 42.1	Cb	α_3	6	8		
S Her	164715	1	+32	7.5	4.7	307	M5e–7	(− 10.7)	− 21.3	Ab	γ_1	11	11	1.6:	
T Her	180531	25	+21	7.8	5.0	165.0	M2e–4e	(−125)	−131	Aa	β_3	11	11		
U Her	162119	3	+39	7.6	4.7	406.2	M7e–8e	(− 22.5)	− 40.4	Cd	α_4–γ_1	7	6	2.0:	
W Her	163137	27	+41	8.2	5.3	279.5	M3e	(− 51)	− 59	Bb	β_1	10	10		
RS Her	171723	13	+28	7.9	4.6	218.7	M5e–6	(− 37.8)	− 50.8	Ab	β_3	10	10		
RT Her	170627	17	+32	9.8	5.2	299	M3e			Cb	α_3	9	8		
RU Her	160625	9	+45	7.9	5.8	478	M7e	(− 15.3)	− 37.6	Cd	α_2–γ_1	6	6	2.2	
RV Her	175519	13	+19	8.8	5.0	222	M4e–6	− 38.9	− 50.1	Ca	β_2	10	9		
RZ Her	183225	22	+13	9.6	5.2	328	M6e			Cb	α_2	10	10	0.7:	
TV Her	181031	26	+20	9.0	)5.0	305.4	M4e			Cb	α_3	8	6		
AE Her	183922	20	+10	9.3	)3.2	245	M6e	(− 48.0)	− 60.4			8	8		
R Hor	025050	231	−57	6.4	7.4	405	M7e			Cb		5	6	3.4	
U Hor	034946	220	−49	8.5	)2.5	348	M6e			Cd		8	8		
R Hya	132422	283	+38	4.2	5.3	405	M6e–9e	− 5.0	− 22.8	Cd	β_1–γ_1	10	8	2.0	R
S Hya	084803	193	+30	7.9	4.9	256	M3e	(+ 78)	+ 70	Aa	β_2	9	9		
T Hya	085008	205	+23	7.9	5.0	289	M3e–4e	(− 3)	− 12	Bd	β_1–γ_1	10	10	2.0	

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
V Hya	104620	237	+34	6.6	2.4	530	N			Ad		4	6		R
W Hya	134327	287	+32	7.1	2.8	385.6	M7e–9e	+ 42.3	+ 26.4		β_1	7	8		R
X Hya	093014	217	+27	8.7	4.1	302	M6e–8e			Cb	α_4	8	8		
RR Hya	094023	225	+23	8.4	)5.6	336.8	M4e			Cc	?	9	5		
RS Hya	104628	242	+28	9.8	4.7	338	M6e			Cb	β_1	8	10		
RT Hya	082405	198	+20	7.1	2.2	254.8	M6e–7	+ 40	+ 35	Aa	Pec.	9	10:		
RU Hya	140528	292	+30	7.5	6.6	334.1	——			Cb		5	6		
RW Hya	132824	284	+36	*8.1*	*1.5*	370	K5e–M2e					7	9		
RY Hya	081403	188	+22	8.3	3.0	535	Nbed					4	7		
R Ind	222867	287	—46	8.9	13.8	216	M2e–3e			Bb	β_2	9	9		
S Ind	204954	310	—41	7.9	6.9	402.7	M6e–7e			Cb	α_2?	4	4		
R Lac	223841	68	—15	8.3	6.3	299.4	M5e	(+ 18.1)	+ 8.2	Cb	α_3	8	7		
S Lac	222439	64	—15	8.2	4.7	240	M5e–6e	— 59.7	— 65.9	Ba	β_2	10	10		
R Leo	094211	192	+45	5.9	4.2	313	M6e–9e	+ 15.0	— 1.8	Bb	α_4	7	9		R
V Leo	095421	180	+52	9.0	4.8	273.2	M4e	(— 22.7)	— 30.8	Cb	α_3	6	9		
W Leo	104814	202	+61	9.4	4.4	385.7	M7e			Cb	α_2	6	7	2.0	
R Lep	045514	182	—30	6.0	4.4	440	N6e			Aa	β_2	6	8		
T Lep	050022	191	—30	7.5	5.5	368.0	M7e	(— 2.8)	— 18	Bd	β_1–γ_1	10	10	1.8	
R LMi	093934	158	+51	7.0	5.8	371.8	M7e–8e	+ 9.5	— 3.1	Cb	α_3	8	9		
S Lib	151520	313	+29	8.5	3.8	192.2	M2e	(+295.3)	+284.6	Aa	β_3	10	10:		R

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
U Lib	1536*20*a	316	+25	9.3	5.0	226.5	M3e			Cc	α_3	10	10		
Y Lib	1506*05*	322	+42	8.3	5.7	275.2	M5e	− 6.9	− 15.0	Cb	α_3	9	9		
RR Lib	1550*18*	321	+25	8.9	5.0	276.1	M4e	(− 32.3)	− 40.6	Bb	α_4	10	10		
RS Lib	1518*22*	312	+26	7.6	4.7	217.6	M7e–8e	(− 2.1)	− 15.1	Ca	β_2	9	10		
RT Lib	1500*18*	311	+32	9.0	)5.4	252	M2e			Bb	α_3	8	8		
RU Lib	1527*14*	319	+31	8.2	5.9	318	M5e–6e	(− 48.2)	− 59.5	Cb	α_4	8	8		
RW Lib	1517*23*	311	+26	*8.6*	*3.1*	203	S5e					9:	9:		
S Lup	1446*46*a	292	+10	8.9	)3.1	346.0	Se					10	8	2.3	
Y Lup	1452*54*	289	+ 3	9.6	4.9	407	M7e			Cb	α_1	6	6		
R Lyn	065355	129	+24	8.0	5.9	379.3	S3e	(+ 34)	+ 11	Bd	β_2–γ_1	10	10	2.2	
S Lyn	063558	125	+23	9.4	4.6	300.5	M6e			Cb	α_2	9	8		
T Lyn	081633	158	+33	8.0	4.0	419	N0e			Cb		7	8		
S Lyr	190925	26	+ 6	9.4	6.1	439.0	Me			Cb	α_2?	8	7		
U Lyr	191637	37	+10	9.6	2.2	458	Ne			Cb		6	4		
V Lyr	190529a	29	+ 8	9.7	5.2	373.8	M7e			Cb	α_2?	7	6:		
W Lyr	181136	31	+22	7.7	4.6	196.4	M4e–5	−174	−183	Ab	β_3–γ_1	10	11		
RS Lyr	190933a	32	+ 9	9.9	5.1	371	Me			Ba	β_1	10	10		
RT Lyr	185737	35	+13	9.3	6.3	251.7	Me			Cb	α_3?	10	8		
RW Lyr	184243	40	+19	9.5	6.0	509	M7e			Cb	α_1	8	8		
RX Lyr	185032	30	+13	11.0	)5.0	250.6	Me			Cb	α_3?	9	10		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
RY Lyr	184134	32	+15	9.6	4.8	327	M5e			Cb	α_3?	8	7		
R Mic	203429	343	−36	9.2	4.0	138.3	M4e			Aa	β_2	10	10		
S Mic	212030	345	−47	9.2	)4.8	213.2	M3e			Bb	β_2?	10	10		
U Mic	202240	328	−36	8.3	5.7	333	M6e–7e			Cb	α_3	8	7		
V Mon	061702	179	− 6	7.2	5.8	334.7	M5e–8e	(+ 29)	+ 16	Cb	α_4	7	8		
X Mon	065208	189	− 1	7.3	1.9	155.3	M3e–4	(+157)	+147.5	Bb	Pec.	10	10		
Y Mon	065111	171	+ 8	9.1	4.3	229.3	M4e			Bc	β	10	9		
R Nor	152849	296	+ 4	7.3	4.6	487.5	M4e–5			D	γ_2	22	18	2.0	
T Nor	153654	294	− 1	7.0	6.0	243.9	M3e–6			Cb	α_3	8	9		
R Oct	055686	265	−29	8.0	4.2	408	M7e			Cd	α–γ_1	6	4	2.0	
S Oct	172486	275	−27	8.7	4.8	259	M4e–5e			Cb	α_3	9	9		
T Oct	205782	277	−33	8.6	3.8	218.0	M2e				α_4?	8	9		
U Oct	131283	272	−21	7.8	5.7	300.5	M4e			Ba	β_1	10	10		
R Oph	170215	334	+13	7.6	6.2	302.2	M4e–6e	(− 49)	− 59	Bb	α_4	10	10		
V Oph	162112	331	+23	7.4	2.8	297	N3eα			Ba		9	9		
X Oph	183308	7	+ 6	6.8	2.0	335.4	M5e–7e	− 70.6	− 83.8	Ca	β_1	7	8		R
Z Oph	171401	351	+19	8.1	4.4	349	M2e	(− 79)	− 93	Ab	α_4	5	10		
RR Oph	164319	328	+15	8.5	4.7	293.0	M3e			Bb	α_4	10	10		
RV Oph	181103	0	+ 8	8.2	4.8	150.7	M4e–5e	(− 67.2)	− 71.8	Ba	α_4–	9	8		
SS Oph	165202	344	+22	9.0	4.2	179.5	M2e	(− 30.3)	− 42.9	Ca	β?	10	9		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
R Ori	045307	160	—19	9.5	3.5	378.5	S1e			Cb	β	8	8		
S Ori	052404	175	—18	7.9	5.3	413.2	M7e			Bd	γ_1	10	11	2.2:	
U Ori	054920a	156	— 1	6.0	5.8	372.2	M6e–8	— 17)	— 37.2	Bb	α_4–γ_1	6	6	3.7	R
V Ori	050003	164	—19	9.4	4.8	271.4	M3e	(+ 21.9)	+ 13.9	Ba		9	10		
W Ori	050001	167	—22	5.9	7.7	200	N5					7::	10::		R
R Pav	180363	298	—21	8.4	4.8	230	M3e–4e			Bb	α_4–β?	10	10		
S Pav	194659	305	—32	7.4	2.6	389	M7e–8			Aa		10	10		
T Pav	193972	290	—32	8.0	5.5	244.1	M3e–4e			Bb	α_3	10	9		
U Pav	204763	300	—39	8.6	4.4	290	M4e				α_3	8	8		
W Pav	174162	298	—18	9.0	4.9	282	M4e			Bb	α_3	8	10		
R Peg	230110	54	—45	7.9	5.1	376.9	M6e–9e			Cb	α_4–γ_1	7	9		
S Peg	231508	58	—48	8.0	5.3	318.8	M5e–8e	(+ 5)	— 7	Cc	α_4–β_1	10	9		
T Peg	220412	41	—35	8.6	5.4	375.3	M6e–7e	(— 8.2)	— 23.9	Bc	β_1	9	6		
V Peg	215605	34	—38	8.6	5.8	302.6	M3e–5e			Cb	α_3	7	7		
W Peg	231425	67	—33	8.1	4.6	342.7	M6e–8e	(— 22)	— 35	Ba	β_1	10	10		
X Peg	211614	34	—25	9.3	4.4	200.5	M2			Bc		10	9	2.0:	
Y Peg	220613	44	—34	10.0	4.5	207.2	M3e			Bb	α_3	8	7		
Z Peg	235525	77	—35	8.4	12.9	321	M6e–7e			Bc	β_2	10	10	2.0:	
RR Peg	214024	46	—22	9.1	4.8	263	M4e			Cb	α_3	8	7		
RS Peg	220714	44	—34	9.0	5.0	414	M6e–7e	(— 20.0)	— 40.0	Cd	α_2	6	9	3.0	

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
		°	°		*m*	*d*									
RT Peg	215934	56	—16	9.7	3.7	215.2	M3e			Bb	Pec.	7	7		
RV Peg	222129	57	—23	9.5	5.5	391	M6e			Cb	α_2?	5	6		
RZ Peg	220133b	56	—18	9.0	3.0	442	Se			Cb		10	10		
R Per	032335	124	—16	8.6	5.3	210.1	M2e–3e	— 78.2	— 89.1	Aa	β	9	10		
U Per	015254	101	— 6	8.1	2.8	318.5	M6e–7e	+ 15	+ 9.9	Ab	α pec.	8	10	0.7:	
W Per	024356	107	— 2	8.9	1.7	496	M9			Ad?	β_3:	5	4:		
Y Per	032043	118	—10	8.4	1.8	250	N3eα			Ba	β_2	8	7		
RR Per	022150	106	— 8	8.9	5.1	391	M6e–7e			Cd	α_1	6	10		
RZ Per	012350	97	—11	8.5	5.2	355.7	——			Ad		12	11	2.3	
R Phe	235150	292	—66	7.5	6.0	268.9	M3e			Cc	β	10	9		
T Phe	002546	278	—71	9.7	4.3	281.0	M5e			Cb	α_2	8	8		
V Phe	232746	303	—67	9.0	)4.0	251	M4e			Ca		10	10		
R Pic	044349	223	—40	6.7	2.5	167	M1e–4e			Ba	γ_2	10	11		
S Pic	050848	222	—36	8.2	5.6	427	M7e–8e			Cb	α_4	5	5		
R Psc	012502	112	—57	8.2	5.5	344	M3e–4e	(— 45)	— 59	Cb	α_3	8	6		
S Psc	011208	103	—52	9.6	5.3	406	M7e			Cb	α_2?	6	6		
L_2 Pup	071044	223	—14	4.0	2.0	140.2	M5e–6	+ 52.6	+ 51	Cb	γ_1?	8	8		
W Pup	074241	224	— 7	8.4	3.8	120.8	M3e			Aa	β_3	8	13		
Z Pup	072820b	204	— 1	7.5	6.5	516.3	M7e	(+ 35.6)	+ 12.6	Cb	α_1?	4	3		
S Pyx	090024	220	+15	8.5	5.3	206.5	M2e			Cb		9	9		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	10 c/d	e/f	Rem.
R Ret	0432*63*	240	−39	7.6	5.6	279.1	M4e			Cb	α_4	10	9		
R Sgr	1910*19*	346	−15	7.3	5.4	269.0	M4e–6e	(− 44.3)	− 52.3	Ca	β	8	9		
S Sgr	1913*19*a	346	−16	10.0	)4.0	230.2	M3e			Cb	β ?	10	10		
T Sgr	1910*17*	348	−14	8.0	4.8	390.2	S4e	(+ 4)	− 19.4	Ca		8	8		
RR Sgr	1949*29*	339	−27	6.6	6.7	336	M4e–6e			Cb	α_4	10	9		
RT Sgr	2011*39*	330	−34	7.2	5.8	302.9	M5e–7e			Bb	α_4–β_1	10	10	2.0	
RU Sgr	1951*42*	325	−31	7.0	5.4	242	M3e–6e				α_4	10	8		
RV Sgr	1821*33*	328	−11	7.8	5.8	319.5	M4e–6e			Ba	β	10	11		
RX Sgr	1908*18*	346	−15	9.4	4.3	332	M5e			Cc	β	10	7	2.0	
ST Sgr	1855*12*a	350	−10	9.4	)5.6	395	M7e			Cb	α_2?	9	8		
SW Sgr	1913*31*	334	−21	10.0	)4.0	289	M5e			Cd		10	10	1.8	
TY Sgr	1911*24*	341	−18	9.8	)4.2	335	M3e			Cb	α_1	8	8		
Z Sco	1600*21*	320	+21	9.1	4.1	353	M7e			Bd	β_2	12	10	2.0	
RR Sco	1650*30*a	321	+ 6	6.0	5.5	279.3	M5e–8e	(− 36.6)	− 45.1	Ca	β_2	9	10		
RS Sco	1648*44*	309	− 2	6.6	5.3	320.7	M5e–8e			Cb	α_4	7	8		
RT Sco	1656*36*	316	+ 2	7.9	7.3	448	M7e			Cb	α_1	8	6		
RU Sco	1735*43*	315	− 8	8.8	4.3	377	M7e			Cd	γ_1	12	12	1.8	
RW Sco	1708*33*	321	+ 2	10.2	)3.8	385	M5e			Cb	α_1?	9	8		
RZ Sco	1558*23*	318	+20	8.8	3.6	161	M4e			Bb	β_2	10	10		
SV Sco	1741*35*	322	− 6	9.9	3.7	256	Me			Ba	β	10	10		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel.		Light Curve		Numerical Parameters of Light Curve			Rem.
								Abs. km/sec	Em. km/sec	C*	L†	10 a/b	10 c/d	e/f	
		°	°		*m*	*d*									
S Scl	001032	322	−82	6.9	6.1	366.7	M4e–8e	(+ 28.4)	+ 13.2	Bd	β_2	11	10	2.0	
R Ser	154615	354	+45	6.9	6.1	357.2	M6e–8e	+ 27	+ 6.9	Bb	α_4–γ_1	8	8		R
S Ser	151714	348	+52	8.5	5.1	366.4	M5e–6e	(+ 13.5)	− 1.9	Cd	γ_1	9	8	2.0	
U Ser	160210	350	+39	8.3	4.5	236	M2e–3e	(− 29.3)	− 39.8	Bb	α_4–β_1	10	10		
R Tau	042209	153	−24	8.9	5.3	324	M5e–7e	(+ 31.3)	+ 19.2	Cb	α_2	8	7		
V Tau	044617	150	−15	9.2	4.6	169.8	M3e–4e			Bb	β_2	9	9		
W Tau	042215	148	−21	9.1	3.6	266.5	M4			Ad	β_3	10	12		
R Tel	200747	320	−34	8.6	5.6	461.4	M5e–7e			Cb	α_2?	6	5		
R Tri	023133	115	−23	6.0	5.5	266	M4e–8e	+ 66.7	+ 59.6	Ba	β_2	9	9		
R Tuc	235265	277	−52	10.2	3.8	286	M5e			Cb	α_4	9	6		
S Tuc	001862	276	−56	8.8	5.8	240.7	M3e–5e			Bb	α_4	6	9		
T Tuc	223462	293	−50	8.1	5.2	250.6	M2e			Bc	β	10	10		
U Tuc	005475	269	−42	8.5	5.6	258.7	M3e–5e			Ba	β_2	10	10		
R UMa	103769	105	+46	7.5	5.5	301.3	M3e–6e	+ 34	+ 23	Cb	α_3	8	7		
S UMa	123961	90	+57	7.9	3.6	225.3	S2e	(+ 2)	− 4.1	Ad	?	10	13		R
T UMa	123160	92	+58	8.0	4.8	256.7	M3e–6e	(− 98.)	−106	Cb	α_3	9	9		
X UMa	083350	136	+39	9.5	4.5	248.6	M3e	(− 81)	− 90	Ca	α_4?	6	5		
Z UMa	115158	102	+59	*8.4*	*1.8*	198	M6e	− 52.6	− 58.4	Aa?	γ_2	10	11	2.0:	
RS UMa	123459	92	+58	8.9	5.0	260.4	M4e–6e			Cb	α_3	9	8		
S UMi	153378	81	+36	8.3	3.2	322.5	M7e	(− 40.7)	− 52.7	Aa	β_2	8	7		

TABLE III, I—*Continued*

Star	Des.	l	b	M	A	Period	Spectrum	Rad. Vel. Abs. km/sec	Rad. Vel. Em. km/sec	Light Curve C*	Light Curve L†	Numerical Parameters of Light Curve 10 a/b	Numerical Parameters of Light Curve 10 c/d	Numerical Parameters of Light Curve e/f	Rem.
		°	°		*m*	*d*									
T UMi	133273	84	+44	9.1	4.3	315	M4e			Cb	β_1	9	7		
U UMi	141567	76	+48	8.3	3.7	326	M6e	(− 31.0)	− 43.3	Aa	β_2	9	8		
R Vir	123307	266	+69	6.9	4.5	145.4	M3e–6e	− 34	− 33	Aa	β_2	10	10		R
S Vir	132706	290	+54	7.0	5.3	376.3	M6e–7e	(+ 11.3)	− 4.7	Cd	α_4	8	8	0.6	
U Vir	124606	275	+68	8.1	4.8	206.7	M3e–5e	− 42	− 58.1	Ac	β	9	11		
V Vir	132202	289	+58	8.6	5.3	250	M3e	(+ 33.7)	+ 25.0	Cb	β_2?	10:	9:		
RS Vir	142205	321	+57	8.0	5.4	351.3	M6e–7e	(− 25.6)	− 40.0	Cb	α_3	8	8		
R Vul	205923a	38	−16	8.0	4.6	136.8	M4e–5e	(− 14)	− 17	Aa	β_2	10	10		

* Campbell, communicated to the writers.

† Ludendorff, Handbuch d. Ap., 6, 99, 1928; Sitz. d. Preuss. Akad. d. Wiss., Phys.-Math. Kl., 20, 3, 1932; Handbuch d. Ap., 7, 627, 1934.

REMARKS

R And	Spectrum, Merrill, P. A., 37, 444, 1929.
R Aqr	See Merrill, Mt. W. Contr. 206, 1921; Mt. W. Contr. 513, 1925.
R Boo	Spectrum, Merrill, P. A., 37, 444, 1929.
R Cas	Spectrum, Merrill, P. A., 37, 444, 1929; Mt. W. Contr. 399, 1930.
T Cas	Spectrum, Merrill and Burwell, Mt. W. Contr. 399, 1930.
T Cep	Spectrum and velocity curve, Merrill, Mt. W. Contr. 200, 1921; 264, 1923; Merrill and Burwell, Mt. W. Contr. 399, 1930.
o Cet	Joy, Mt. W. Contr. 311, 1926; Merrill and Burwell, Mt. W. Contr. 399, 1930.
χ Cyg	Spectrum and velocity curve, Merrill, Mt. W. Contr. 200, 1921; 264, 1923; Merrill and Burwell, Mt. W. Contr. 399, 1930.
R Cyg	Merrill and Burwell, Mt. W. Contr. 399, 1930.
R Gem	Merrill and Burwell, Mt. W. Contr. 399, 1930.
R Hya	Spectrum and velocity curve, Merrill, Mt. W. Contr. 200, 1921; 264, 1923; Merrill and Burwell, Mt. W. Contr. 399, 1930.
V Hya	Two superimposed periods.
W Hya	Spectrum, Merrill and Burwell, Mt. W. Contr. 399, 1930.
R Leo	Spectrum and velocity curve.
S Lib	Radial velocity excessive.
X Oph	Visual double; see Merrill, Mt. W. Contr. 200, 1921; 261, 1923; 264, 1923.
U Ori	Spectrum, Merrill and Burwell, Mt. W. Contr. 399, 1930.
W Ori	Light curve and spectrum resemble those of V Hydrae.
R Ser	Spectrum, Merrill, Mt. W. Contr. 200, 1921; Merrill and Burwell, Mt. W. Contr. 399, 1930.
S UMa	Spectrum, Merrill and Burwell, Mt. W. Contr. 399, 1930.
R Vir	Merrill and Joy, Mt. W. Contr. 382, 1929.

CHAPTER IV

THE GREAT SEQUENCE, II
THE CEPHEID VARIABLES

All that I know
    Of a certain star
Is, it can throw
    (like an angled spar)
Now a dart of red,
    Now a dart of blue. . .
Browning

The general term "Cepheid" refers to a large and varied group of stars, of which the original prototype, δ Cephei, is a happy representative, being an average specimen in almost all properties that are shown by these stars as a class. Like the long-period variables, the Cepheids are difficult to define precisely, and many stars fall in the disputed territory between the two classes.[1] In the present chapter we regard as a Cepheid any star, with a period less than a hundred days, that is an intrinsic variable of regular behavior and variable spectrum, and that does not fall in the class of long-period variables. This treatment throws together the Cepheids of long and short period (greater and less than one day), in contrast to the arrangement adopted by most other writers; but in view of the fact that the Cepheids of longer period are themselves probably not a single group, it seems to be unjustifiable to collect the short-period Cepheids in a separate class. The properties of all the stars considered in the present chapter are strictly parallel, and they form the most natural group known among the variable stars.

In Prager's catalogue for 1936 there are 598 stars that fulfil the above definitions. Most of these stars are, however, so faint that little is known of them excepting their periods, and in some cases the general form of their light curves. When a selected list of well-observed Cepheids is prepared (Tables IV, I and IV, II), it appears that a relatively small number has been thoroughly studied. It seems to be true that while the light curves of the long-period variables are better known than their spectra (largely through the labors of the amateur astronomical observers), the spectra of Cepheids have been more thoroughly studied than their light curves.

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[1] See Chapter V.

32. General Characteristics of Cepheid Variables.—As with the long-period variables, the richness of the available data compels a selection among the facts known about the Cepheids. The arrangement of the present section will, on the whole, be kept parallel to that of Section 29, where the general properties of the long-period variables are discussed.

i. *The Period-Spectrum Relation.*—It is for the Cepheids that the relation between period and spectrum is best known, and on the whole best marked. The dispersion of the relation between period and median spectrum is considerable,[2] especially for the Cepheid variables of average period (five to fifteen days). As the periods are usually known to within a fraction of a day, and the spectra are subject to no very great uncertainty, at least for the brighter stars, there can be no escape from the reality of the large dispersion. The dispersion for the long-period variables is definitely smaller than that for the Cepheids, when spectral class is considered; if effective temperature is taken as the unit, the smallness of the dispersion for long-period variables seems even more striking. It should, however, be remembered that very few long-period variables have been spectroscopically observed near their minima, the available spectroscopic data rarely being recorded more than three magnitudes below maximum.

The average period-spectrum relation for Cepheid variables, derived graphically from the data of Table IV, I and Table IV, II, is given in Table IV, III. The last three entries contain, for comparison, the relation between spectrum and mean period for several "intermediate" stars (grouped according to

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[2] Payne, The Stars of High Luminosity, 232, 1930.

spectrum, in contradistinction to the rest of the table), which are specially discussed in Chapter V.

The columns of Table IV, III contain respectively the average period; the logarithm of the average period; the average *maximal* spectrum, obtained from a critical study of all the relevant data given in Prager's catalogue for 1936, with the number of stars used following the spectrum, in parentheses; and the average *median* spectrum, derived graphically from the material of Tables IV, I, and IV, II. For periods from one to thirty-three days there is evidently a progression of average spectrum with period. The last three entries show that although for still longer periods the average spectrum is of later type, there is no longer a regular progression of period with spectrum. If the first entry (which includes only one star, CY Aquarii), is not considered, it is seen that for periods less than a day there is no progression of spectrum with period, although the aver-

TABLE IV, III

PERIOD AND SPECTRUM FOR CEPHEID VARIABLES

Period Average *d*	log $\overline{P}$	Average Maximal Spectrum	Average Median Spectrum
0.06	—1.22	B8(1)	A1 :
0.12	—0.92	A5(2)	A7.0
0.35	—0.46	A3(8)	
0.45	—0.35	A7(15)	
0.55	—0.26	A5(11)	
0.64	—0.19	A4(5)	
0.72	00.14	A3(1)	
1.7	0.23	F2(2)	F4
2.4	0.38	F4(10)	F6.5
3.6	0.56	F6(13)	F9
4.4	0.64	F7(18)	G0
5.3	0.72	F9(20)	G1
6.4	0.81	F7(13)	G2
7.5	0.88	F8(11)	G3
8.7	0.94	G0(12)	G3.5
10.9	1.03	G1(11)	G4
13.5	1.13	G2(8)	G5
17.2	1.23	G2(14)	G6
33.0	1.52	G0(10)	G8
79.0	1.90	G3(7)	..
77.0	1.88	K3(1)	..
79.0	1.90	M2.5(16)	..

age spectrum is always of earlier type than for stars with periods greater than a day (A5 for an average period $0^d.46$). The absence of a period-spectrum relation for periods less than a day is confirmed by Shapley's study[4] of the colors of cluster-type variables in Messier 15 and Messier 5. It finds a parallel in the breakdown of the progression of period with luminosity for the same group of stars. It is, however, not impossible that the Cepheids of period greater than a day consist of several distinct groups, within any one of which the progression of spectrum with period may be small. We shall return to this point when the light curves and frequency of periods have been analyzed.

The period-spectrum relation forms the closest link between the Cepheids and the long-period variables. Probably it is the most obvious consequence of a relation between period and mean density—the type of relation that is basic to theories that attribute the variation to a pulsation, or to some other gravitationally governed dynamical cause. The somewhat uncertain data concerning the mean densities of the stars of the Great Sequence lead to the relation

$$P \sqrt{\varrho} = 0.2,$$

which represents approximately the whole sequence from the average cluster type stars to the long-period variables[5]. The departure of the individual cluster-type stars from the general relationship, as indicated by the breakdown of the period-luminosity and period-spectrum relations within that group, presents an interesting problem[6]; but it is neither impossible nor unlikely that the type of difference that may thus be indicated between cluster type stars of long and short period may also occur among Cepheids of longer period. There is a possibility that the long-period variables with periods of about 220 days may bear the same relationship to the other long-period variables as the cluster-type variables bear to the Cepheids of longer period; but with the difference that there is a greater overlap in period between the two groups of long-

[4] Star Clusters, H. Mon. No. 2, 58, 59, 1930.
[5] Russell, Dugan, and Stewart, Astronomy, 2, 774, 1926.
[6] Shapley, H. C., 315, 1927.

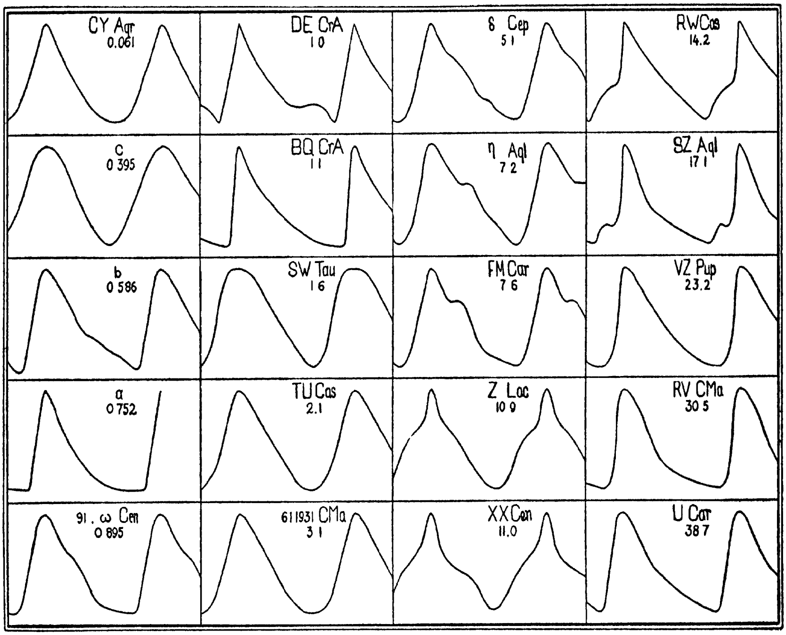

Figure IV, 1—Mean photographic light curves for typical Cepheid variables, arranged in order of period. All are reduced to the same scale, both of ordinates and of abscissae. Sources of the light curves are as follows: CY Aquarii, S. Gaposchkin, H.B. 898, 1935. Cluster type variables of Bailey's classes c, b, and a, Shapley, Star Clusters, p. 54, 1930. Star No. 91 in ω Centauri, Bailey, H. A., 38, 2, 1902. DE and BQ Coronae Austrinae, B.A.N. 243, 1933. SW Tauri, TU Cassiopeiae, XX Centauri, Robinson, H. A., 90, No. 2, 1932. 61. 1931 Canis Majoris, VZ Puppis, RV Canis Majoris, Florja, Publ. Sternberg Astr. Inst. No. 8, 1937. δ Cephei (photoelectric), Stebbins, *see* Russell, Dugan, and Stewart, p. 760, 1927. η Aquilae, (photoelectric), Wylie, *see* Handbuch d. Ap. 6, 189, 1928. FM Carinae, Z Lacertae, RW Cassiopeiae, and U Carinae, Hertzsprung, B.A.N. 96, 1926.

TABLE IV, IV

RELATION OF LIGHT CURVE TO PERIOD FOR GALACTIC CEPHEIDS

Average Period	Parameters of Light Curve 10 *a/b*	 10 *c/d*	 10 *e/f*	Number of Stars
d				
0.06	6	3		1
0.28	6:	8:		4
0.38	5	4		2
0.47	4	4		14
0.55	3	3.4		46
0.65	4	6		19
0.73	5	7		6
1.0	4	3	2	2
1.8	10	9		2
3.0	7	6		11
5.0	5	5	5	25
7.0	5	7	5	23
8.5	6	11	5	2
9.5	11	12	18,6	4
11.0	10	10	20,7	11
13.0	9	9	25,8	7
15.0	5	6	20	6
17.0	5	6	20,5	7
19.0	5	4	25	2
25.0	3	5		8

TABLE IV, V

RELATION OF LIGHT CURVE TO PERIOD FOR VARIABLES IN CLUSTERS

Cluster	Average Period	Parameters of Light Curve 10 *a/b*	 10 *c/d*	 10 *e/f*	Number of Stars
	d *d*				
Messier 3	0.25–0.44	8.5	9.0		20
	0.45–0.54	5.0	4.0	3.0	80
	0.54–0.69	4.0	4.0	3.0	53
Messier 5	0.23–0.35	10.0	10.0		8
	0.42–0.74	4.0	5.0		80
Messier 15	0.30–0.44	6.0	8.0		27
	0.57–0.76	4.0	4.0		29
Messier 53	0.24–0.39	10.0	10.0		14
	0.53–0.71	4.0	6.0		17
ω Centauri	0.30–0.49	10.0	10.0		31
	0.49–0.71	4.0	4.0		50
	0.73–0.87	4.0	8.0		11

period variables than there is between the two groups of Cepheids, which are separated by a definite drop in frequency of period.[7]

ii. *Relation of Period to Light Curve.*—It was shown by Hertzsprung in 1926 that there is a definite relationship between the period of a Cepheid and the occurrence of humps in the light curve[8]. There is a lamentable lack of homogeneity in the published light curves of Cepheids, but a critical study of all the available curves (both published, and a few unpublished Harvard curves), that are well enough determined to enable the form to be examined, fully substantiates his conclusion. In order to express the relationship numerically, the properties of the light curves are expressed, in Tables IV, I and IV, II, in terms of the three ratios, a/b, c/d, and e/f, already described and used in Chapter III[9]. The long tables contain only stars for which reliable light curves and spectra are available, and the present discussion therefore reposes on more stars than are contained in Tables IV, I and IV, II, notably the faint Cepheids in Carina, whose light curves appear in Hertzsprung's paper. Table IV, IV shows the relation of form of light curve to period for galactic Cepheids, including those of period less than a day.

TABLE IV, VI

LIGHT CURVE AND PERIOD FOR ALL CLUSTER TYPE VARIABLES*

Average Period	Parameters of Light Curve $10\,a/b$	 $10\,c/d$	 $10\,e/f$
d			
0.35	9.0	10.0	6.4
0.50	4.5	4.0	2.2
0.60	4.0	5.0	1.7
0.70	4.0	6.0	1.6
0.80	4.0	8.0	1.5:

*Determined graphically. Galactic variables included.

Among the cluster-type variables in any one cluster it has long been known that period is closely related to form of light curve, the most symmetrical light curves (10 *a/b* and 10 *c/d* approaching 10) being associated with the shortest periods. But the departure from symmetry does not increase uniformly with increasing period, for we find values of 10 *a/b* near to 10 again at periods of about a day, and they are most conspicuous of all at periods of about ten days. It was probably this absence of a *continuous* progression in shape of light curve with period throughout all the Cepheids that caused Robinson[10] to conclude that "if any relation exists between period and light curve, it is slight".

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[7] Gaposchkin, S., P.N.A.S., 28, 1, 1938.

[8] B. A. N., 3, 115, 204, 1926.

[9] See Section 28.

But the shape of the light curve is very definitely related to some other properties of the Cepheids, in particular to one of their most significant characteristics—the frequency of periods.

It may be seen that maxima of the quantity *a/b* occur for periods just greater than the minima of period frequency, and that maxima of *c/d* seem to coincide with minima of period frequency. In other words, for periods a little *greater* than the breaks in the period frequency, the light curves tend to be most symmetrical about both axes; long minima, associated with sharp rises in brightness, occur for periods somewhat *shorter* than these minima of frequency.

A relation between shape of light curve and period has already been demonstrated for the Cepheids by Parenago and Kukarkin[11], who found a break in properties at a period of nine days, and noted a minimum of period frequency at the same point.

Such considerations divide the Cepheids into at least three groups. The first, with periods shorter than the break in frequency (which we may now place at about $1^d.6$, instead of at $1^d.0$, as has been tacitly done in the past) embraces the so-called cluster-type variables (Robinson's Type A) and includes the few stars known with periods between $1^d.0$ and $1^d.6$, such as BQ Coronae Austrinae and DE Coronae Austrinae. The second group extends from the minimum in frequency at $1^d.6$ to the next minimum at about nine days, and includes Robinson's Type B Cepheids. Within this group the light curve proceeds from the symmetry shown by SU Cassiopeiae (P = $1^d.95$) to the sharp rise and long minimum of W Sagittarii (P = $7^d.59$). The third group includes stars with periods greater than nine days, showing symmetry for ζ Geminorum (P = $10^d.15$) and Z Lacertae (P = $10^d.89$), down to the strong asymmetry of the light curves of stars such as T Monocerotis (P = $27^d.01$); these stars cover Robinson's Type C Cepheids. Within this period group there are two maxima to the light curve (denoted by the two values given in Table IV, IV for e/f). The second maximum is no longer evident for stars with periods greater than 25 days, where we may look for the beginnings of Robinson's Type D (period greater than 28 days); but apparently this group of stars is not cut off by a distinct minimum of frequency, nor do the light curves pass through another symmetrical stage near a period of 28 days. So far as the light curves of Cepheids of still longer period are known, high asymmetry and long minima persist up to the longest periods, such as those of SV Vulpeculae, RS Puppis, and the long-period Cepheids in the Magellanic Clouds.

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[10] H. A., 90, 82, 1933.

[11] Zs.f.Ap., 11, 337, 1936; Rus. A. J., 14, 181, 317, 1937; Mirovédénie 26, 22, 1937.

There is a distinct minimum in frequency of period between eighty and a hundred days, and for periods slightly longer than this (the long-period variables of shortest period) a return to a symmetrical light curve is seen again (see Table III, II). We recall that among the long-period variables themselves, the asymmetry of the light curve tends to increase towards the longest periods. Here again there is an indication that the long-period variables have something in common with the Cepheids.

In Table IV, IV the entries for the shortest periods are marked as uncertain, for the dispersion of the quantities a/b and c/d is there unusually large. We note that the two galactic cluster-type variables of shortest known period (CY Aquarii, $P = 0^d.06$; and KU Centauri, $P = 0^d.08$) both have highly asymmetrical light curves. It is not impossible that they belong to the long-period end of another group of Cepheids of exceedingly short period, and that the small number of periods of the order of a tenth of a day is an indication of another minimum of period-frequency.

Although the period-spectrum relation appears at first sight to bridge smoothly the breaks in frequency at one and at ten days, a more careful scrutiny of the material suggests, at least, that the breaks in frequency and symmetry are accompanied by breaks in spectral class, and that the apparent smoothness is caused in reality by slight overlapping of the different groups. The data are not as yet complete or precise enough; but the point deserves some attention.

Since these results seem to be important and comparatively well established we give a brief summary of them, to which we add some other results published elsewhere by one of the writers.*

1. There are five minima of frequency of period along the Great Sequence: in the intervals of period $0^d.17$—$0^d.25$; $1^d.45$—$1^d.65$; $8^d.50$—$9^d.45$; $55^d.0$—$65^d.0$; and 550^d—650^d.
2. There are five corresponding maxima of frequency: at $0^d.12$: ; $0^d.5$: ; 5^d: ; 12^d: ; and 290^d: .
3. Between any two minima of frequency the light curves run, with increasing period, from symmetry to asymmetry.
4. At the minima of frequency the light curves show the greatest irregularities.
5. The hump on the descending branch moves back from the lowest position on the light curve ($P = 6^d.0$) towards the maximum with increasing period; it reaches the maximum at about $9^d.5$, and then moves down on the ascending branch until it disappears at a period of about 27^d.
6. The hump moves in the opposite direction with increasing period in the interval between $0^d.34$ and $0^d.74$: that is, for the shortest periods it is near the maximum, and moves down the descending branch towards minimum with increasing period.
7. There seems to be no doubt that where there is an overlap in form of light curve between two groups of stars separated by a minimum of period-frequency, there is also an overlap in spectral characteristics.
8. There is some evidence of a break in the period-luminosity relation at the second and third minima of frequency.

The data concerning the Cepheids in systems other than the galaxy are not very numerous, but, such as they are, they indicate that form of light curve bears the same relation to period, wherever the star may be situated. Roughly speaking, this seems to be the case for the cluster-type stars in individual globular clusters (see Table IV, V), although the period of minimum frequency, and also the period of departure from the symmetry of Bailey's Type c light curve, seem to differ slightly from cluster to cluster[12]. That period and form of light curve are very similarly related for stars of longer period may be seen by comparing Table IV, VII (which combines data from several extragalactic systems and globular clusters) with Table IV, IV. Maximum symmetry occurs at about the same period of ten days, and in this period interval even the characteristic double maximum is shown by stars in the Small Magellanic Cloud[13].

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* Pop. Astr., Aug.-Sep., 1938, *in press.*

TABLE IV, VII

LIGHT CURVE AND PERIOD FOR CEPHEIDS IN EXTRAGALACTIC SYSTEMS

Limits of Period	Parameters of Light Curve *a/b*	*c/d*	*e/f*	Contributing Systems	Number of Stars
d *d*					
0.5– 0.6	7.0	4.0		N. G. C. 6723	4
1.0– 5.0	7.0	7.0		Small Mag. Cloud	19
9.0–14.0	10.0	11.0	20,5	Messier 31, Small Mag. Cloud, ω Centauri	3
20 –26	5.0	6.0		Messier 5, Messier 31 Messier 33, N. G. C. 6822	6
31 –46	4.0	6.0		Messier 31, Messier 33 N. G. C. 6822, ω Centauri	6

iii. *The Period-Luminosity Curve.*—The relation between period and absolute magnitude is the most obvious and best-studied correlation between properties of the Cepheid variables, and is indeed so well established that a detailed documentation would be out of place. It should be noted that there are two distinct phases of the problem: first, the establishment of the relation itself, which has been carried out primarily by studying the Magellanic Clouds and a few other systems that can be treated as units in respect to distance; secondly, the determination of the zero point, which must be done either statistically, by use of the galactic Cepheids for which radial and transverse motions can be measured, or indirectly, by determination of the distance of the external systems in which Cepheids are found by methods independent of the period-luminosity relation. It is around the second phase of the problem that the greater part of

[12] Miss Sawyer, H. C. 366, 1931.
[13] *Cf.* Robinson, H. A., 90, 92, 1933.

the controversies have raged. The most complete treatment of the problem, up to 1930, is that given by Shapley[14] in his monograph on star clusters, where the history of the subject is briefly covered, and where the classical references will be found. We may consider that at the present time the relative period-luminosity curve is accurately determined, and that the zero point is subject to a small correction, if any. The coordinates of the photographic period-luminosity curve, taken directly from Shapley's monograph, are reproduced in Table IV, VIII. The shape of the period-luminosity curve for long-period Cepheids was discussed by Kukarkin (Rus. A. J., **14**, 125, 1937), who on the basis of 349 extragalactic Cepheids has found that the relation is satisfied by two straight lines: $\overline{M} = -0^m.62 - 1.30 \log P$, for $\log P < 0.97$; and $\overline{M} = -0^m.47 - 1.73 \log P$, for $\log P > 0.97$.

TABLE IV, VIII

THE PHOTOGRAPHIC PERIOD-LUMINOSITY CURVE

Logarithm of Period	Absolute Photographic Magnitude	Logarithm of Period	Absolute Photographic Magnitude
—0.6	0.00	+0.8	—1.53
—0.4	0.00	+1.0	—1.89
—0.2	—0.07	+1.2	—2.26
0.0	—0.31	+1.4	—2.68
+0.2	—0.61	+1.6	—3.19
+0.4	—0.93	+1.8	—3.81
+0.6	—1.22	+2.0	—4.60

The results of a number of attempts to investigate the zero point of the period-luminosity curve are summarized by Ludendorff[15] and by Gerasimovič[16]. Several investigators, including Adams, Joy and Humason[17], Kipper[18], Cecchini[19], LiHen[20], and, in particular, Gerasimovič[21], have concluded that a correction of about $+1^m.0$ should be made for zero point.

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[14] Star Clusters, Chapter 10, 125-134, 1930; for later discussions, see Kukarkin and Parenago, Variable Stars, 71, 1937.

[15] Handbuch d. Astrophys., 6, 664, 1928.

[16] Course of Astronomy and Astrophysics, 2, 386, 1935.

[17] P. A. S. P., 41, 252, 1929.

[18] A. N., 241, 249, 1931.

[19] Contr. Astr. Merate, No. 14, 1931.

[20] C. R., 195, 601, 1932.

[21] A. J., 41, 17, 1931.

Mention should also be made of discussions by Lundmark, the first of which indicated a large correction, the second, however, a much smaller one[22]. The most recent discussions of the possible correction to the zero point of the period-luminosity curve have tended to reduce the estimates just quoted; Gerasimovič[23], by making allowance for absorption of light in low galactic latitudes, is able to bring his results into agreement with the luminosities of cluster-type stars as deduced from their motions; for example, Mrs. Bok and Miss Boyd[24] have concluded on this basis that no correction to the zero point of the period-luminosity curve is necessary. Other investigators, for example Fletcher[25], Parenago[26], and Nassau[27], have reached the conclusion that the correction, if any is required, amounts to less than half a magnitude.

How general is the applicability of the period-luminosity relation? Are Cepheid variables of similar period strictly comparable, wherever they occur? That their light curves are similar has been tentatively concluded in the preceding section. It is not yet possible to show precisely whether the zero points of the period-luminosity relations that have been determined in different systems are exactly the same. The *relative* period-luminosity relations determined for several systems are always in good general agreement, as was shown by Shapley[28] (for the Small Magellanic Cloud, ω Centauri, and Messier 3, 5, and 15) and later by Miss Sawyer[29] (for all the globular clusters known at the time to contain Cepheids of long period). Hubble[30] has derived similar relative period-luminosity curves for Messier 31 and 33 and for N. G. C. 6822. The magnitude scales that form the basis of period-luminosity relations for the Large and Small Magellanic Clouds have been recently compared by Miss Mohr[31]; the differences in zero point and scale are apparently

[22] Lund Medd., Series 2, No. 60, 1931; VJS, **68**, 369, 1933.
[23] Obs., **57**, 22, 1934; Course of Astronomy and Astrophysics, **2**, 388, 1935.
[24] H. B. 893, 1933.
[25] M. N., **95**, 56, 1934.
[26] R. A. J., **11**, 31, 1934.
[27] A. J., **44**, 33, 1934.
[28] Star Clusters, 129, 1930.
[29] H. C. 366, 1931; Pub. Dom. Ap. Obs., **6**, 281, 1929.
[30] Mt. W. Contr. 304, 1925; *ibid.*, 310, 1926; *ibid.*, 376, 1929.
[31] H. A., **105**, No. 11, 1936

small—not much greater, indeed, than possible systematic errors in the standard magnitudes. In all discussions of magnitudes and moduli of distant systems, especially those depending on the measurement of faint objects, it should be remembered that by far the greatest observational difficulty with such data is the determination of accurate magnitudes. For stars fainter than the eighteenth magnitude there are possibly systematic errors in even the best standards; and in the southern hemisphere there are few reliable standards (especially in regard to systematic error) fainter than the fifteenth magnitude. When this point is kept in mind it appears that there is no certain evidence of real differences in the period-luminosity curves determined for different stellar systems, either in scale or zero point.

iv. *Distribution of Cepheid Variables.*—The Cepheids of period greater than a day are very strongly concentrated toward the Milky Way; the mean galactic latitude for those north of the galactic plane is $+5^\circ.6$ (63 stars), and for those south of the galactic plane, $-5^\circ.3$ (132 stars). The mean galactic latitude of the long-period variables, on the other hand, is 28°, indicating a negligible galactic concentration, in sharp contrast to the Cepheids of longer period. The distribution of Cepheids in galactic longitude is somewhat irregular, with a maximum frequency in the direction of Carina and Crux. There is another group in Cassiopeia, at about galactic longitude 90°, and smaller groups are found in Sagittarius (galactic longitude 340°), and in Canis Major and Puppis (galactic longitude 200°). There are also two isolated groups of faint Cepheids in high latitude: one is in Hydrus (R Hydri, RZ Hydri, ST Hydri), the other in Virgo (XX Virginis, AL Virginis, and W Virginis). The close concentration of the long-period Cepheids to the galactic plane is partly an index of high luminosity, but probably also represents a real tendency to lie near the plane. The long-period Cepheids thus differ from the long-period variables in distribution, both in galactic latitude and in galactic longitude.*

*See a discussion on this point by Parenago and Grigorieva (Russ. A. J., 14, 329, 1937).

The galactic cluster-type variables are found freely in high galactic latitudes[32]; the observed distribution is so far a function of selectively searched areas that a discussion of the galactic distribution of faint cluster-type variables would be meaningless at the present time.

v. *Motions of Cepheid Variables.*—The Cepheids are sharply divided into two groups, with periods greater and less than a day, when their motions are compared.[33] The average peculiar velocity for Cepheids with periods greater than a day is about 12 km/sec, according to Strömberg[34], and for 93 such Cepheids Joy[35] finds an average radial velocity of 22 km/sec. On the other hand, Cepheids with periods less than a day have average peculiar velocities of about 70 km/sec; and from 51 such stars Joy finds an average radial velocity of 100 km/sec. Between the stars of periods less than $8^d.5$ and more than $9^d.5$ there is a less evident break, but the average radial velocity for the former is 13.4 km/sec (16 stars) and for the latter, 9.8 km/sec (8 stars). The high average radial velocity of the long-period variables, especially those of shorter period, should be contrasted.[36]

33. Properties of Individual Stars.

33. Properties of Individual Stars.—The two lists of Cepheid variable stars, Tables IV, I and IV, II, contain the Cepheids that are reasonably well known in light curve and in spectrum. The light curves of a number of typical Cepheids are shown in Figures IV, 1, and IV, 2. The β Canis Majoris stars, which are discussed at the end of the present chapter, appear to be closely allied to the Cepheids proper, but their light curves are too ill defined for general illustration.

i. *Spectra and Spectral Changes.*—The spectral variations of most Cepheids are very uniform and similar. Both line spectrum and distribution of energy correspond to a higher effective temperature at maximum than at minimum, and they alter continuously throughout the cycle of variation of brightness. The range in spectrum is, roughly at least, proportional to the range in brightness.

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[32] Shapley, H. Repr. 118, 1936; P. N. A. S., 22, 8, 1936.

[33] See Ludendorff, Handbuch der Astrophysik, 6, 213, 1928.

[34] Ap. J., 61, 363, 1925.

[35] P. A. S. P., 44, 240, 1932.

[36] See Section 29, v.

The most important data on the colors of Cepheids are of course the spectrophotometric studies of the distribution of energy throughout the observable spectrum. Hitherto the chief contributions to this branch of observation have been those of Hopmann[37], ten Bruggencate[38], Gyllenberg[39], Whipple[40], and M. Schwarzschild[41]. Color curves, determined from the change of color index throughout the period by comparing two mean light curves not determined simultaneously, add but little to our present knowledge that the color curve is parallel to the light curve, the star being always bluest at maximum, reddest at minimum light. They are, however, of some interest as substitutes for the spectra of faint variables, and a careful study of the color curves of a group of related stars (such as the Cepheids in the Magellanic Clouds) should convey important information, supplementing the period-spectrum relation, that is not directly attainable from a study of galactic Cepheids. If a color curve is to have real significance, it must be determined from simultaneous observations at the two wave-lengths compared, or at least the observations in the two colors should be concurrent, covering the same cycles. Color curves determined from a comparison of mean light curves made by different observers, usually with different (and unknown) degrees of precision, at different times, may lead to serious misinterpretation. For example, Okunev[42] drew the conclusion from such material that secondary waves in the light curve are reproduced in the color curve, although many of the secondary waves in his light curves themselves are evidently unreal. Such conclusions are not, however, necessarily erroneous, for Gyllenberg's study of S Sagittae shows that the color curve has a marked secondary minimum, as has also the light curve. Furthermore, it is not appropriate to draw conclusions as to differences in time of maximum or minimum for light of different colors, unless the observations are simultaneous, since individual maxima and minima may depart slightly from a uniform ephemeris. The color curves determined by one of the writers[43] are free from the objection just made, for they are obtained by simultaneous (automatic) exposures made on red and blue plates. If actual differences in time of maximum and minimum in light of different colors are found, they denote that maximum light does not coincide with maximum effective temperature, nor minimum light with minimum effective temperature; but conclusions on this point should obviously be drawn rather from spectrophotometric measures than from comparisons of light curves[44]. In the rising and falling atmosphere of a Cepheid we have a case so much less simple than that of the atmosphere of a non-varying star, that the crude idea of one changing effective temperature is clearly inadequate.

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[37] A. N., 221, 337, 1924; *ibid.*, 222, 1, 233, 1924; *ibid.*, 226, 1, 1925; *ibid.*, 227, 257, 1926.

[38] Ann. Bosscha Sternw., 2, C3, 1928.

[39] Lund Medd., Series 2, No. 24, 1920.

[40] L. O. B. 442, 1932.

[41] Zs. f. Ap., 12, 171, 1936; see also Brück and Strohmeier, Zs. f. Ap., 13, 13, 1936; *ib.*, 13, 317, 1937; Becker, Zs. f. Ap., 13, 69, 1936; *ib.*, 13, 313, 1937.

[42] A. N., 236, 313, 1929.

The variations of the line spectra of Cepheids run parallel to the variations of the energy distribution; the spectral class is earliest at maximum, latest at minimum light, and the average change of spectrum is about one spectral class between maximum and minimum (see Tables IV, I and IV, II). Though the individual Cepheid is of latest spectral class at the part of the cycle where it is faintest, the Cepheids of latest median spectral class are the brightest absolutely. The more careful studies of spectrum and energy distribution show that both spectrum and effective temperature differ slightly at points of the same apparent magnitude on the rising and falling branches of the light curve.

The spectra of many Cepheid variables that are bright enough to show the line quality display the c-character[45], and the stars must accordingly be regarded as very luminous. In general, their high luminosity is most strikingly shown by the relative intensities of the lines, for although for some, notably

[43] S. Gaposchkin, H. B. 898, 900, 1935.
[44] See Tiercy, Arch. des Sci., 15, 127, 1933.
[45] Shapley and Payne, H. B. 872, 1930.

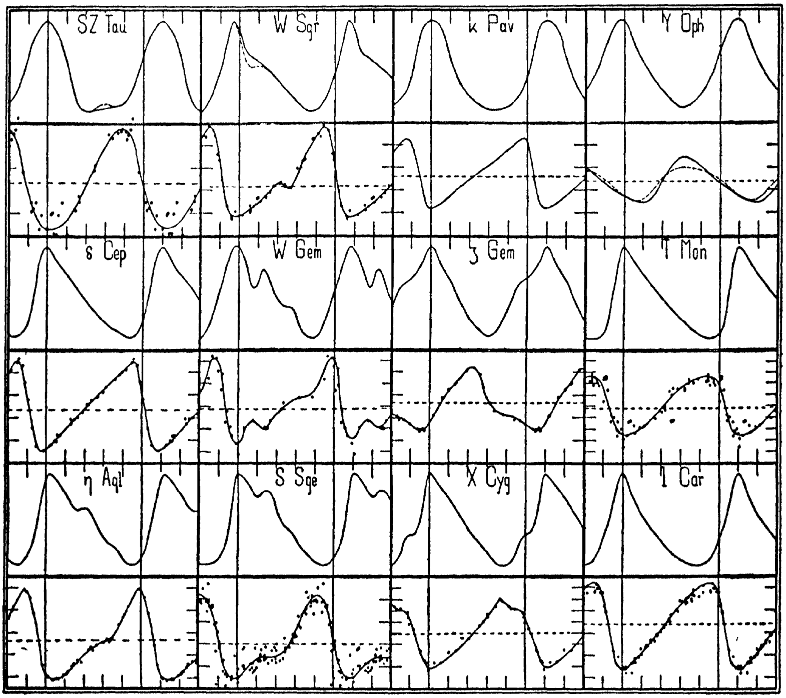

Figure IV, 2.—Comparison of light curves and velocity curves for twelve typical Cepheid variables. All light curves are reduced to the same scales of ordinates and abscissae. Velocity curves are all reduced to the same scales of abscissae; short horizontal lines on the left and right indicate intervals of 10 kilometers per second in radial velocity. Broken horizontal lines indicate the systemic velocities as follows: SZ Tauri, —3.15 km/sec; δ Cephei, —16.83 km/sec; η Aquilae, —14.16 km/sec; W Sagittarii, —28.6 km/sec; W Geminorum, —0.70 km/sec; κ Pavonis, +36.5 km/sec; ζ Geminorum, +6.8 km/sec; X Cygni, +9.32 km/sec; Y Ophiuchi, —6.1 km/sec; T Monocerotis, +4 km/sec; l Carinae, +4.08 km/sec.

Sources of light curves: SZ Tauri, W Sagittarii (full curve), W Geminorum, ζ Geminorum, X Cygni, l Carinae, Robinson, H. A., 90, 58, 1932. δ Cephei, Stebbins, *see* Russell, Dugan, and Stewart, p. 760, 1927. η Aquilae, Wylie, *see* Handb. d. Ap., 6, 189, 1928. S Sagittae, T Monocerotis, Hertzsprung, B.A.N. 96, 1926. W Sagittarii (broken curve) and basic data for κ Pavonis, Shapley, Proc. Am. Acad. Sci., 64, 11, 1930. Y Ophiuchi, ten Bruggencate, Bosscha Ann., 2, B 53, 1927.

Sources of velocity curves: SZ Tauri, Haynes, L.O.B., 8, 85, 1913. δ Cephei, η Aquilae, W Sagittarii, and ζ Geminorum, Jacobsen, L.O.B. 379, 1926. W Geminorum, Sanford, Ap. J., 72, 46, 1930. S Sagittae, Jacobsen, L.O.B. 393, 1928. κ Pavonis, Jacobsen, L.O.B., 14, 60, 1929. X Cygni, Duncan, Ap. J., 53, 95, 1921. Y Ophiuchi, Sanford, Ap. J., 81, 140, 1935. T Monocerotis, Sanford, Ap. J., 66, 174, 1927. l Carinae, Jacobsen, P.A.S.P., 46, 255, 1934.

Phases of light curves and velocity curves have been rendered comparable by reducing with the same elements and referring to the same initial epoch.

those of longest period, the line contours have the typical sharp edges associated with the c-character, the lines of all Cepheids become wider towards minimum, often presenting a shallow and hazy appearance, which has never been interpreted.[46]

ii. *Velocity Curves.*—The stars for which velocity curves and spectroscopic elements have been determined are indicated in the notes to Tables IV, I and IV, II; in addition, limiting radial velocities are given for other stars of undetermined spectroscopic elements. In Figure IV, 2 the velocity curves and light curves are shown for a number of stars. The validity of the general relationship, that the velocity curve is a mirror image of the light curve, may be judged from the figure. In the opinion of the authors, the correspondence is close.

The recent summary of a study of the radial velocity curves of 128 Cepheids by Joy[47] strengthens this conclusion. His relation between asymmetry of the velocity curve and period is similar to the relation described above between asymmetry of light curve and period. The most asymmetrical velocity curves are found in the neighborhood of minima of period frequency.

Ever since good light curves and spectroscopic elements have been available, it has been clear that Cepheid variability cannot be interpreted in terms of orbital motion. When the spectroscopic elements are compared with those of typical eclipsing variables, a striking contrast is evident: the average value of the half-amplitude, K, of the velocity curve, is 16 km/sec for twenty-four Cepheids, including one cluster type star; whereas for the average of fifty-two eclipsing systems[48] it is 123 km/sec.

Another important point of contrast is that for the eclipsing stars belonging to the same spectral classes, the value of K is smaller, the longer the period, while for the Cepheids with periods greater than a day there is no such tendency—indeed it seems as though larger values of K go with longer periods.

The correlations between light curves and velocity curves have been critically studied by Robinson and Hoffleit[49]. After a careful discussion of the data for twenty-one stars (including RU Camelopardalis), they concluded that the maxima and minima of light and velocity curves are not always coincident; the light curve tends to precede the velocity curve in four cases, distributed apparently at random in period.

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[46] Payne, The Stars of High Luminosity, 215, 1930. See also F. Beileke, Z. f. Ap., 14, 1, 1937.

[47] Ap. J., 86, 435, 1937.

[48] See Section 20.

More recently Joy[50] has examined the lag of maxima and minima of the velocity curves of 128 Cepheids with respect to minima and maxima of their light curves. He concludes that there is "apparently an increase of lag with lengthening period up to periods of about 30 days, beyond which it falls off considerably."

Comparisons of light curves with velocity curves should strictly be made from observations covering the same interval of time, and from this standpoint there is much work still to be done. Fugitive changes in the light curve of Y Sagittarii, for example, were accompanied by changes in the velocity curve[51].

iii. *Light Curves.*—The forms of the light curves of Cepheid variables have been discussed in an earlier section. Variations of light curve have been reported for several stars. Isolated changes in brightness, confirmed by several observations made on the same night, have been demonstrated by ten Bruggencate[52] for Y Sagittarii, and by Bernheimer[53] and Mustel and Severny[54] for η Aquilae. Probably such irregularities in the form of the light curve, taking the shape of short-lived minima of brightness, would be found to be not uncommon if more detailed studies were made of a number of individual Cepheids.

Another type of variation in the light curve involves irregularity in the form of the rising curve, noted, for example, by Robinson[55] for TU Cassiopeiae. This type of variation may be described as an unusual unpunctuality in the moment of rise of brightness; O'Connell, in connection with his study of VX Puppis and UZ Centauri, has suggested that this tendency may

[49] H. B. 888, 1932.

[50] Ap. J., 86, 435, 1937.

[51] Ten Bruggencate, H. C. 351, 1930.

[52] Lembang Ann., No. 3, 198, 1928.

[53] Lund Medd., Series 2, No. 61, 1931.

[54] R. A. J., 7, 125, 1930.

[55] H. B. 866, 1929.

be particularly marked in the neighborhood of minima of period-frequency[56]. The most obvious example is furnished by the semiregular variables (associated with the minimum of frequency between 60 and 100 days); but V389 Cygni[57] ($P = 1^d.13$) and AI Velorum[58] ($P = 0^d.11$) furnish examples corresponding to two other minima of frequency. A fruitful field of investigation is here indicated.

Changes in the form of the mean light curve have been reported by Robinson[59] for XY Cassiopeiae, BF Ophiuchi, XX Sagittarii, X Sagittarii, and W Sagittarii. Parenago and Kukarkin, however, consider[60] that there is as yet no reliable evidence of changes in shape (mean light curve). Isolated variations, at least, are well substantiated, and individual rises and maxima are certainly different at different epochs for BF Ophiuchi and for the cluster-type star, RR Lyrae. Whether the reported changes in *mean* light curve are real appears doubtful to the authors.

Observations of changes in the shape of the light curves of cluster-type stars have been made[61], but both observations and interpretation are very difficult, and not infrequently two observers will obtain differing light curves even for the same interval of time.

Changes of period for Cepheids and cluster-type stars have been the subjects of much work and speculation. Ludendorff[62] has summarized recent observational work, which has been especially emphasized in the researches of Zessewitsch[63], Kukarkin[64], and Florja[65]. A particularly interesting case is that of RW Draconis, recently shown[66] by Balázs and Detré to have several superposed variations of different periods.

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[56] Riverview Obs. Circ., No. 1, 1935; No. 2, 1936.

[57] Guthnick, Abh. d. Preuss. Akad. d. Wiss., No. 3, 1938.

[58] Zagar, B. A. N. 300, 1937; van Hoof, B. A. N. 300, 1937.

[59] H. B. 872, 1930; H. A., 90, 60, 1933.

[60] Zs. f. Ap., **11**, 337, 1936.

[61] See, for example, S. Gaposchkin, H. B. 898, 1935.

[62] Handbuch der Astrophysik, 7, 658, 1936.

[63] A. N., 231, 249, 1927; Leningrad Ephem. 5, 1935; Tadjik Circ. 8, 1935.

[64] Gorki Bul., 4, 269, 1934; Zs. f. Ap., 4, 247, 1932.

[65] A. N., 242, 289, 1931; Zs. f. Ap., 4, 247, 1932.

[66] Abhand. des Astroph. Observatoriums Budapest, No. 5, 1938.

Extensive discussions have been made of changes in period for cluster-type stars in two globular clusters: those in Messier 3 by Müller[67], and those in ω Centauri by Martin[68]. Both Müller and Martin found approximately equal numbers of "increasing" and "decreasing" periods—as did Kukarkin and Florja[69] when discussing the same problem for galactic Cepheids. Although the changes of period are almost at the limit of detectability, they are probably real; in particular, Martin has shown that the observed changes are too large to be attributed to chance.

34. The Beta Canis Majoris Stars.—A group of stars that is probably to be associated with the Cepheids comprises a number of variables of very short period, small amplitude, and intermittent variation of velocity. Henroteau was the first to assemble a list of possible members of the group[70], and a number of other investigators have since contributed to their study. Table IV, IX gives a list of the stars that have been assigned to the class, and indicates briefly the nature of the data concerning each star. Those that are regarded as doubtful members are indicated by parentheses; seventeen stars remain as possible Beta Canis Majoris stars.

Of the seventeen probable members of the group, six have been shown to have periodic variations of radial velocity; all the periods but one are very short—less than a third of a day. Ten of the stars retained in the group are noted as variable in light, and when periodic velocity variations are known for the same stars, the periods are approximately the same. The amplitudes of light variation never exceed a quarter of a magnitude, and often fall within a tenth of a magnitude, so that the stars are almost exclusively photoelectric objects.

The spectra range from Class B1 to Class F4, and the periods (with one exception, ε Ursae Majoris) from $0^d.11$ to $0^d.31$. The relation between period and spectrum is shown in Table

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[67] Veröff. Ber.-Bab., 11, No. 1, 1933.

[68] Dissertation, Leiden, 1937.

[69] Zs. f. Ap., 4, 247, 1932.

[70] Handbuch d. Astrophys., 6, 436, 1928.

IV, X. The shorter periods are related to spectra of later type, a contrast to the period-spectrum relation for Cepheids and cluster-type stars, but a parallel to the W Ursae Majoris stars[71]. The obvious interpretation is that the β Canis Majoris stars are members of the main sequence rather than giant stars, a suggestion borne out by the fact that the spectra of seven of them (all those of Class A0 and later, excepting ϵ Ursae Majoris) bear the suffix n, indicative of hazy lines[72].

The hazy lines and the period-spectrum relation parallel to that for the W Ursae Majoris stars might suggest that the members of the present group, too, are binary systems. But the large variations in amplitude of radial velocity are difficult to reconcile with orbital motion (see, for example, the data for 12 Lacertae), and it seems more probable that the β Canis Majoris stars are intrinsic variables, a view that has long been held by Henroteau and others.

The breakdown of the period-spectrum relation becomes less mysterious if we regard that relation, in a general way, as a joint result of the dependence of period on mean density, and the statistical correlation of mean density with spectral class. The latter correlation has, of course, two branches—the giant and dwarf branches of the spectrum-absolute magnitude diagram—and though for the giant branch decreasing density goes with advancing spectrum, this relation is reversed along the main sequence.

If the β Canis Majoris stars are assumed to have mean densities appropriate to main-sequence stars of their spectral classes, their periods are in line with the period-density relation for cluster-type variables and long-period Cepheids, as Eddington[73] showed long ago for β Cephei (not, however, a happy example, for the data concerning this star are still inadequate and doubtful). The point is illustrated by the last four columns of Table IV, X. The two so headed contain the mean densities of main sequence stars of the spectral types given in the first column, on the basis of the average properties of stars in general, and the properties of eclipsing stars (brighter component of system)[74]. The last two columns give the mean densities, computed from the periods of the stars given in the second column, on the basis respectively of the values 0.2 and 0.12 for the quantity $P\sqrt{\rho}$. It will be seen that the observed and computed densities are of the same order.

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[71] See Section 23.

[72] See Parenago, R. A. J., 11, 37, 1934.

[73] The Internal Constitution of the Stars, 1926.

TABLE IV, X

SPECTRUM, PERIOD, AND DENSITY FOR BETA CANIS MAJORIS STARS

Spectrum	Mean Period	Stars	Logarithm of Mean Density		Logarithm of Computed Mean Density	
			Normal Stars	Eclipsing Stars	$P\sqrt{\rho}=0.2$	$P\sqrt{\rho}=0.12$
	d					
B1	0.23	3	—1.12	—0.98	—0.12	—0.57
B2	0.23	3	—1.07	—0.82	—0.12	—0.57
A0.5	0.24	2	—0.63	—0.47	—0.16	—0.50
A2.5	0.20	3	—0.54	—0.41	0.00	—0.44
F2	0.16	3	—0.39	—0.28	+0.19	—0.27

The star ε Ursae Majoris is outstanding: its period is three times as long as those of the other stars in the list, and its spectrum bears the suffix s, denoting sharp lines. It is a member of the Ursa Major group, and therefore not a supergiant; but it may well have a larger diameter and lower mean density than the other stars enumerated.[75]

Another star very probably belonging to the β Canis Majoris group is V389 Cygni, for which Guthnick has found remarkable variations of light curve and of velocity curve[76]. Its period is $1^d.13$; its spectrum of Class A0 (Harvard), B8 (Victoria).

It is very possible that the two groups of erratic periodic variables just mentioned, one with periods of about a quarter of a day, the other, of about a day, represent the irregular behavior that appears to occur near minima of frequency of period. They are, in fact, the short-period semi-regular variables.

There are a few other variable stars that are possibly members of, or allied to, the group now under discussion. The well-known supergiant of Class A2, α Cygni, has variations of radial velocity[77], of spectral line form[78], and of color[79]; for this star the period, if any, seems to be of the order of two-tenths of a day.

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[74] See Section 18.

[75] For this remark we are indebted to Professor Russell.

[76] Abh. d. Preuss. Akad. d. Wiss., Phys.-Math. Kl., No. 3, 1938.

It is suggestive that another star that shows indications of high luminosity, α Canum Venaticorum, has periodic variations ($P = 5^d.46$) of radial velocity[80], spectrum[81], and brightness[82], and that the spectroscopic elements have the earmarks of a Cepheid (notably a low mass function and a value of ω near to 90°). This star is without doubt a variable; its regularity of period and its continuous variation place it in the Great Sequence, and it seems as closely related to the present group as to any other.

Another possible member of the group is RW Aquilae—its variable radial velocity, its small or non-existent light variation, the fact that a period has never been determined, and its spectrum (F3n) all seem to point to an association. Procyon, though once suspected of variations of radial velocity, is not, however, to be included in the group[83].

All the members now assigned to the β Canis Majoris group are of bright apparent magnitude, and the inference may be drawn that this type of stellar variability is actually common. It will perhaps be convenient to think of, and refer to, them as "dwarf Cepheids", as a reminder that they may preponderate over the other Cepheids as the dwarfs preponderate over the giants. But stars of such small ranges can be detected only photoelectrically, and probably the growth in the number of stars assigned to the class cannot be very rapid, even if its members are common in space.

[77] Paddock, L. O. B. 472, 1935.

[78] Unpublished spectrophotometric observations of one of the writers.

[79] Greaves, Davidson, and Martin, Observations of Colour Temperatures of Stars, Royal Observatory, Greenwich, p. 54, 1932.

[80] Belopolsky, A. N., 196, 6, 1913; Kiess, Publ. Obs. Mich., 3, 106, 1923.

[81] Miss Anger, Ap. J., 70, 114, 1929; Miss Goldena Farnsworth, Ap. J., 75, 364, 1932 (Miss Farnsworth concludes that the radial velocity is constant, and attributes its observed variations to blending).

[82] Güssow and Guthnick, Kl. Veröff. Ber-Bab., No. 8, Star No. 268, 1930.

[83] Albrecht, Ap. J., 80, 86, 1934; Schaub, Zs. f. Ap., 9, 198, 1934.

TABLE IV, I

SELECTED LIST OF GALACTIC CEPHEIDS

Star	Designation	l	b	M	A	Period	log P	Spect.	Light Curves 10 a/b	 10 c/d	 10 e/f	Limits of Radial Velocity *km/sec*	Notes
		°	°		*m*	*d*							
U Aql	192407	358	−13	6.32	0.69	7.02	0.85	G0–G6	5	6	5	41.6	1, 28
SZ Aql	185901	3	+ 1	*9.39*	*1.96*	17.14	1.23	G1–K5	4	2	20	−22.7 +45.4	2, 28
TT Aql	190301	7	−12	*8.36*	*1.20*	13.75	1.14	G0–K3	4	9	35	−26.5 +27.4	2, 28
FF Aql	185317	18	+ 7	*6.4*	*0.5*	4.47	0.65	F5	4	7	. .	14.2	3, 28
η Aql	194700	7	−16	3.69	0.71	7.18	0.86	F2–G9	5	9	5	41.7	4, 28
Y Aur	052142	134	+ 5	*9.82*	*1.05*	3.86	0.59	F2–G5	7	4		−12.7 +32.5	28
RT Aur	062230	150	+ 8	*5.37*	*1.18*	3.73	0.57	F1–G5	3	4		—	5, 28
RX Aur	045439	133	− 2	*7.96*	*1.08*	11.62	1.06	G0–K0	9	9	30	−32.1 − 5.6	2, 28
SY Aur	050542	144	+ 4	*9.82*	*1.17*	10.14	1.00	G0–G2	11	9	20	−13.6 +12.6	28
YZ Aur	050839	135	+ 1	*11.16*	*1.10*	18.20	1.26	G0–K	6	4	25	−49.1 + 4.2	28
RU Cam	071069	114	+28	7.8	1.2	22.17		Rp					6
RW Cam	034658	112	+ 4	*8.95*	*1.41*	16.41	1.21	G4	5	6	5:	−52.1 +10.6	28
RX Cam	055658	113	+ 5	*7.62*	*1.66*	7.91	0.90	G2–K2	4	11	6	−57.5 −10.6	28
U Car	105359	255	+ 1	6.30	1.25	38.75	1.59	F8–K5	5	5		—	
V Car	082659	242	−12	7.4	0.7	6.70	0.82	G2–K0	5	5		—	
Y Car	102957	255	+ 3	*8.83*	*0.70*	3.64	0.56	F5	4	6		—	
SX Car	104257	255	+ 3	*9.32*	*0.97*	4.86	0.69	F5–K0	4	5		—	
UW Car	102359	253	− 2	*10.00*	*1.06*	5.35	0.73	G	5	5		—	
WZ Car	105160	257	0	*8.52*	*1.62*	23.00	1.36	F8	2	5		—	
XX Car	105364	259	− 4	*8.47*	*2.17*	15.72	1.20	G5	4	6	20	—	

TABLE IV, I—*Continued*

Star	Designation	l	b	M	A	Period	log P	Spect.	Light Curves 10 a/b	Light Curves 10 c/d	Light Curves 10 e/f	Limits of Radial Velocity *km/sec*	Notes
		°	°		*m*	*d*							
XY Car	1058*63*	258	— 3	*9.2*	*1.5*	12.43	1.09	K	9	9	25	—	
AQ Car	1018*60*	254	— 3	*9.2*	*0.8*	9.77	0.99	G0	11	16	23, 7	—	
ER Car	1105*58*	258	+ 2	*7*	*1*	7.72	0.88	F8	6	12	5	—	
l Car	0942*62*	250	— 5	3.6	1.2	35.52	1.55	F8–K0	6	4		40.3	7, 28
RS Cas	233261	75	+ 2	*10.26*	*1.35*	6.29	0.80	G5	6	4		—47.6 — 9.4	28
RW Cas	013057	95	— 4	8.82	1.00	14.80	1.17	G2–M	4	7	20	—97.1 —42.6	28
RY Cas	234758	82	— 5	9.3	0.9	12.14	1.08	G2–K	10	8		—90.5 —49.8	28
SU Cas	024368	101	+ 9	6.05	0.38	1.95	0.29	F2–F9	10	9		22.0	8, 28
SW Cas	230258	78	— 3	*10.24*	*1.25*	5.44	0.73	G0–K0	5	8		—54.0 —24.9	28
SY Cas	000957	87	— 4	*10.05*	*1.32*	4.07	0.61	F8–G5	5	3		—60.0 —11.2	28
SZ Cas	021959	103	— 1	9.65	0.42	5.16	0.71	G1	10	10	27	—59.3 —24.3	28
TU Cas	002050	86	—11	*7.90*	*1.17*	2.14	0.33	F5–G2	5	6		35.1	9, 28
VV Cas	014459	96	— 3	*10.79*	*0.99*	*6.21*	0.79	G	5	6	5	—64.1 —41.1	28
XY Cas	004459	90	— 3	9.71	0.69	4.50	0.65	F8–K	9	9		—55.6 —26.8	28
V Cen	1425*56*	283	+ 3	6.32	0.96	5.49	0.74	F5–G7	5	5		—	
XX Cen	1333*57*	278	+ 5	*6.58*	*2.06*	10.96	1.04	F5–K0	10	10	15, 6	—	
AY Cen	1120*60*	260	0	*10.3*	*1.0*	5.30	0.72	K0	5	6		—	
AZ Cen	1120*60*	260	0	*9.6*	*0.4*	3.21	0.51	G0	8	7		—	
δ Cep	222557	72	0	*3.71*	*0.72*	5.37	0.73	F4–G6	4	5		—37.5 + 7.9	10, 28
R Cru	1218*61*	268	+ 2	6.58	0.73	5.83	0.77	F8–K0	5	8	5:	—	

TABLE IV, I—*Continued*

Star	Designation	l	b	M	A	Period	log P	Spect.	Light Curves 10 a/b	10 c/d	10 e/f	Limits of Radial Velocity *km/sec*	Notes
		°	°		*m*	*d*							
S Cru	124857	269	+ 5	6.39	0.72	4.69	0.67	F5–G8	3	5		—	
T Cru	121561	288	0	6.58	0.41	6.73	0.83	G0–G5	5	7		—	
X Cru	124058	266	+ 3	*8.5*	*0.5*	6.21	0.79	G0–K0	8	7		—	
X Cyg	203935	43	— 3	*6.53*	*1.56*	16.39	1.21	F8–K0	6	6	20:	56.1	11, 28
SU Cyg	194029	31	+ 3	6.37	0.71	3.85	0.59	F0–G1	4	4		47.0	12, 28
SZ Cyg	202946	52	+ 4	8.88	0.81	15.11	1.18	G5–K7					
TX Cyg	205642a	53	— 3	9.17	1.02	14.71	1.17	K2–K7	4	5	2.0	—36.4 — 1.4	28
VX Cyg	205339	49	— 4	9.65	1.11	20.14	1.30	Rp	8	4	2.5	—50.9 + 4.1	28
VY Cyg	210039	50	— 5	9.54	0.65	7.86	0.90	K	5	6		—26.2 + 9.2	28
VZ Cyg	214742	60	—10	*9.15*	*1.24*	4.86	0.68	F5–G5	6	6		—32.6 + 1.4	2, 28
CD Cyg	210039	37	+ 1	*9.38*	*1.41*	17.07	1.23	G0–K2	5	3	0.5	—47.0 +24.2	28
DT Cyg	210230	45	—12	5.66	0.39	2.50	0.40	F5	6	8		17.0	28
β Dor	053262	238	—32	*4.24*	*1.45*	9.84	0.99	F2–F9	10:	10:		37.0	13, 28
W Gem	062915	165	+ 5	*7.05*	*0.94*	7.91	0.90	F6–G5	5	8	0.6	33.4	14, 28
RZ Gem	055622	154	0	*10.42*	*1.42*	5.53	0.74	F5–G5	5	5		—11.7 +13.3	28
ζ Gem	065820	163	+12	3.73	0.37	10.15	1.00	cGlv	10	10	1.5	28.5	15, 28
V Lac	224455	74	— 3	*8.78*	*1.18*	4.98	0.70	F2–G5	4	5		—45.6 + 1.3	28
X Lac	224555	74	— 3	*8.88*	*0.61*	5.44	0.74	G1–G5	9	9		—42.6 —16.2	28
Y Lac	220550	66	— 5	*9.29*	*0.89*	4.32	0.64	F8	6	6		—50.0 + 5.3	28
Z Lac	223656	74	— 2	*8.64*	*1.36*	10.89	1.03	F8–K2	9	9	2.2, 7	—43.5 + 4.8	2, 28

TABLE IV, I—*Continued*

Star	Designation	l	b	M	A	Period	log P	Spect.	Light Curves 10 a/b	10 c/d	10 e/f	Limits of Radial Velocity *km/sec*		Notes
		°	°		*m*	*d*								
RR Lac	223755	73	− 3	*8.92*	*1.15*	6.42	0.81	F5–K	5	6	4	−51.1	−16.4	28
BG Lac	215643	60	−10	*9.35*	*1.01*	5.33	0.73	F7–G4	5	7	4	−36.0	− 5.3	28
T Mon	061907	172	− 1	5.80	0.95	27.01	1.43	F8–K0	4	5		50.5		16, 28
SV Mon	061606	180	− 8	8.2	0.8	15.23	1.18	F8–K5	3	9		− 2.1	+60.0	28
R Mus	123668	270	− 7	5.90	1.30	7.51	0.88	F8–G5	4	12	5	—		
S Mus	120769	267	− 8	6.22	0.76	9.66	0.98	F8–G5	10	12	6	48.		28
S Nor	161057	297	− 5	*7.19*	*0.66*	9.75	0.98	F8–G2	10	10	13, 8	37.0		28
U Nor	153454	295	0	*9.91*	*1.36*	12.64	1.10	G0–K5	10	10	20, 7	—		
Y Oph	174706	347	+10	*7.17*	*0.97*	17.12	1.23	F8–G7	7	8		19.8		17, 28
BF Oph	165926	324	+ 8	*7.63*	*1.14*	4.07	0.61	F8–K2	8	4		−54.6	−11.5	28
RS Ori	061614	164	0	*8.70*	*1.10*	7.57	0.88	F2–G0	3	7		+19.8	+78.6	2, 28
κ Pav	184667	295	−26	4.18	0.96	9.11	0.96	F5–G5	9:	8:		31.0		18, 28
SV Per	044242	130	0	*9.36*	*1.13*	11.13	1.05	F8–K0	9	4	18	−27.2	+ 8.6	2, 28
VX Per	020057	100	− 4	*10.11*	*0.74*	10.90	1.04	G0	14	9	18	−46.9	−19.1	28
X Pup	072820a	203	0	*8.38*	2.00	25.97	1.41	F5–K2	3	6		+25.2	+97.1	28
S Sge	195116	23	− 6	*5.79*	*1.02*	8.38	0.92	F8–G7	5	10	6	41.1		19, 28
U Sgr	182619	341	− 4	*7.96*	*1.15*	6.74	0.83	F8–K0	4	9		−21.9	+16.3	2, 28
W Sgr	175829	330	− 4	*4.73*	*1.42*	7.59	0.88	F2–G6	4	4		41.7		20, 28
X Sgr	174127	329	− 1	*4.84*	*1.05*	7.01	0.84	F5–G9	5	6		30.4		21, 28
Y Sgr	181518	340	− 3	*5.68*	*1.14*	5.77	0.76	F5–G8	7	7		36.6		22, 28

TABLE IV, I—*Continued*

Star	Designation	l	b	M	A	Period	log P	Spect.	Light Curves 10 a/b	10 c/d	10 e/f	Limits of Radial Velocity *km/sec*		Notes
		°	°		*m*	*d*								
WZ Sgr	1811*19*	340	− 2	*8.12*	*2.34*	21.85	1.34	G0–K5	5	2	20:	−43.2	+16.3	2, 28
XX Sgr	1819*16*	343	− 2	*9.27*	*1.63*	6.42	0.81	F8–K0	4	7		−25.7	+32.3	28
YZ Sgr	1843*16*	346	− 8	*8.08*	*0.72*	9.55	0.98	G2–K2	12	12		+ 2.8	+40.0	2, 28
AP Sgr	1806*23*	336	− 3	*6.69*	*1.86*	5.06	0.70	F5–K0	5	5		− 3.6	−34.9	28
BB Sgr	1845*20*	343	−10	*7.60*	*1.01*	6.64	0.82	F8–K0	6	7		−18.9	+31.3	28
RV Sco	1651*33*	318	+ 5	*7.03*	*1.10*	6.06	0.78	F5–G5	5	5		−39.1	+ 6.5	28
RY Sco	1744*33*	325	− 5	*8.36*	*1.12*	20.31	1.31	F8–K0	6	7		−40.5	+ 2.2	28
X Sct	1825*13*	345	− 2	*10.67*	*1.14*	4.20	0.62	F5–K2	6	5		−12.6	+25.0	28
Y Sct	1832*08*	352	− 1	*10.69*	*1.03*	10.34	1.01	G2–K7	10	10		−18.8	+20.8	28
Z Sct	1837*05*	354	0	*10.15*	*1.82*	12.90	1.11	G0–M0	9	9	8:	+ 9.8	+50.5	28
RU Sct	1836*04*	356	0	*10.41*	*1.40*	19.70	1.29	G5–M	4	3		−39.3	+15.1	28
SS Sct	1838*07*	353	− 3	*8.70*	*1.22*	3.67	0.56	F8–G5	6	7		− 2.4	−23.5	28
ST Tau	1845*13*	160	− 7	*8.49*	*1.10*	4.03	0.61	F5–G5	4	6		−22.3	+18.0	28
SW Tau	1848*12*	155	−30	*9.27*	*1.57*	1.58	0.20	F3	10	10		− 5.8	+44.0	28
SZ Tau	043118	147	−18	*6.78*	*0.60*	3.15	0.50	F4–G2	10	8		21.3		23, 28
R TrA	1510*66*	285	− 7	*7.07*	*1.11*	3.39	0.53	F5–G5	5	5		32.0		24, 28
S TrA	1552*63*	288	− 8	*6.44*	*1.39*	6.32	0.80	F5–K0	5	8		38.0		28
U TrA	1558*62*	291	− 1	*7.96*	*0.88*	2.57	0.41	F2–G5	6	6		—		
α U Mi	012288	89	+24	2.08	0.09	3.97	0.59	cF7v	6:	7:		—		25
T Vel	0834*47*	235	− 2	7.65	0.85	4.64	0.67	G0–G5	3	4		—		

TABLE IV, I—*Continued*

Star	Designation	l	b	M	A	Period	log P	Spect.	Light Curves 10 a/b	10 c/d	10 e/f	Limits of Radial Velocity *km/sec*	Notes
		°	°		*m*	*d*							
V Vel	091955	245	− 4	*7.07*	*0.88*	4.37	0.64	F8–G5	7	5		—	
RY Vel	101654	250	+ 3	*9.95*	*0.77*	28.13	1.45	G2–K2	4	6		—	
RZ Vel	083343	231	− 1	*6.6*	*2.6*	20.39	1.31	K0				—	
SV Vel	104055	252	+ 2	*8.4*	*1.8*	14.10	1.15	F5–K2	5	5	25	—	
SW Vel	084047	235	− 3	*7.5*	*2.35*	23.51	1.37	K2	4	6		—	
SX Vel	084145	233	− 2	*8.34*	*1.45*	9.55	0.98	G5	9	10		—	
W Vir	132002	289	+62	9.48	1.26	17.27	1.24	cG0p				−94. −33.4	2, 28
T Vul	204727	55	+ 1	5.45	0.87	4.44	0.65	F3–G5	6	6		35.3	26, 28
U Vul	193220	25	− 1	*7.71*	*1.15*	7.99	0.90	F8–K0	6	10	6	37.6	27, 28
X Vul	195326	30	0	*9.45*	*0.68*	6.32	0.80	G0–K5	6	10		−30.5 +12.8	29
SV Vul	194727	28	+ 5	*8.43*	*0.90*	45.13	1.65	G2–M0	4	4		−27.6 +23.5	29

1. Sanford, Ap. J., 72, 46, 1930.
2. Adams and Joy, P. A. S. P., 36, 139, 1924.
3. Sanford, Ap. J., 81, 132, 1935.
4. Wright, Ap. J., 9, 66, 1899.
5. Duncan, L. O. B., 5, 121, 1909.
6. Neilsen, A. N., 260, 377, 1936.
7. Jacobsen, P. A. S. P., 46, 255, 1934.
8. Adams and Shapley, Ap. J., 47, 46, 1918.
9. Sanford, Ap. J., 68, 169, 1928.
10. Moore, L. O. B., 7, 153, 1913.
11. Duncan, Ap. J., 53, 95, 1921.

FOOTNOTES TO TABLE IV, I—*Continued*

12. Hellerich, A. N., 210, 68, 1919.
13. Applegate, L. O. B., 13, 12, 1927
14. Sanford, Ap. J., 72, 46, 1930.
15. Campbell, Ap. J., 13, 93, 1901.
16. Sanford, Ap. J., 66, 174, 1927.
17. Sanford, Ap. J., 81, 144, 1935.
18. Jacobsen, L. O. B., 14, 60, 1925.
19. Aldrich, Pop. Astr., 32, 218, 1924.
20. Curtiss, L. O. B., 3, 36, 1904.
21. Moore, L. O. B., 5, 111, 1909.
22. ten Bruggencate, H C. 351, 1930.
23. Haynes, L. O. B, 8, 85, 1913.
24. Hellerich, A. N., 219, 169, 1923.
25. Kholodovsky, L. O. B., 11, 166, 1924; Color curve, M. Schwarzschild, Zs. f. Ap., 12, 171, 1936.
26. Beal, D. O., 3, 198, 1915.
27. Sanford, Ap. J., 67, 326, 1928.
28. Joy, Ap. J., 86, 363, 1937.

TABLE IV, II

SELECTED LIST OF GALACTIC CLUSTER TYPE VARIABLES

Star	Designation	l	b	M	A	Period	Spect.	Parameters 10 a/b	 10 c/d	 10 c/f	Radial Velocity Limits km/sec	Rem.
		°	°		*m*	*d*						
SW And	001282	84	—34	9.26	1.06	0.44227	A3–F8	3	5	2.5	— 42 + 9	1
XX And	011138	97	—24	10.23	0.75	0.72274	A3–F5	3	8	1.5		
SW Aqr	211*000*	20	—32	10.82	1.17	0.45930	A3	5	5	3.0	— 56 + 15	1
SX Aqr	213102	27	—37	10.9	1.7	0.53571	A2	6	4	2.5		
CY Aqr	223201	25	—38	10.0	0.7	0.06104	B8–A3	7	4	3.0		
S Ara	1751*49*	311	—13	*9.97*	*1.13*	0.45189	A3–F5	7	8	3.0		
X Ari	030310	135	—39	9.06	0.63	0.65112	A0–A7	4	4	1.9		
RS Boo	142932	19	+66	9.48	1.10	0.37734	A3–F4	5	4	3.5	— 56 + 19	1
SW Boo	142336	24	+55	*11.01*	*1.51*	0.51351	A	6	4	3.0		
TV Boo	141242	45	+*67*	*10.3*	*1.1*	0.31256	B9	5	6	4.0		
W CVn	140238	35	+70	*9.82*	*1.02*	0.55176	A7–F5	4	9	3.3	+ 15 + 25	1
Z CVn	124544	90	+74	*9.25*	*1.13*	0.65380	A5	6	6	2.0:		
RV Cap	2055*15*	1	—48	9.2	1.3	0.44775	A8	5	4	3.5	—121 — 51	1
RZ Cep	223564	*67*	+14	8.95	0.80	0.30869	A0–A3	7	7	7.1	— 42 14	1
RR Cet	012700	114	0	*9.19*	*1.12*	0.55302	F0	5	5	3.0	—144 — 59	1
RV Cet	2352*09*	55	—68	10.75	0.80	0.62340	F	5	6	2.0		
UY Cyg	205230	42	—11	10.37	0.98	0.56070	F0	6	6	2.7	— 39 — 33	1
XX Cyg	200158	60	+14	*11.39*	*1.06*	0.13487	A	4	4	3.6		
XZ Cyg	193056	55	+17	9.04	0.92	0.46659	A0–A8	5	5	2.5	(—196)	2
RW Dra	163358	55	+40	10.1	1.0	0.44290	A5	4:	5:	2.5:	—124 — 94	1, 6

TABLE IV, II—*Continued*

Star	Designation	l	b	M	A	Period	Spect.	Parameters			Radial Velocity Limits km/sec		Rem.
								10 a/b	10 c/d	10 e/f			
		°	°		*m*	*d*							
SU Dra	113267	100	+49	*9.45*	*0.97*	0.66042	A2–A5	3	7	1.8	−195	−152	1
SW Dra	121370	95	+48	9.72	1.03	0.56967	F4	7	8	1.8	− 70	+ 12	1
RX Eri	044515	180	−33	*8.8*	*0.8*	0.58724	F0	5	6	2.0:	+ 46	+ 86	1
RR Gem	071531	155	+21	10.7	1.0	0.39726	A8	5	4	3.5	+ 44	+ 95	1
TW Her	175030	23	+24	9.95	1.72	0.39960	F1	4	4	4.0			
VX Her	162618	2	+38	*9.5*	*2.0*	0.45537	A3	5	5	3.0	−405	−375	1
RR Leo	100224	176	+54	9.82	1.53	0.45238	A0–F2	6	5	3.0:	+ 9	+ 58	1
V LMi	101929	171	+60	10.1	1.2	0.54391	A	3	4	2.0			
U Lep	045221	148	−12	9.88	1.29	0.58147	A4	5	4:	..	+ 90	+139	1
RR Lyr	192242	42	+11	7.16	0.79	0.56685	B9–F2	5	4	1.8	Vel. curve		3
RZ Lyr	183932	29	+15	11.02	1.25	0.51126	A2	5	5	2.0	−281	−161	1
TU Per	030152	111	− 4	11.4	0.8	0.60708	A5s	5:	4:	1.8:	(−350)		4
AR Per	041047	122	− 1	9.84	0.83	0.42555	G0	6	3	3.0			
RU Psc	010823	80	−39	10.05	0.47	0.39040	A3	6	6	5.0:			
RU Scl	235725	10	−79	*9.8*	*0.9*	0.49333	A0	7	4	2.2			
VY Ser	152602	335	+43	9.50	0.69	0.41632	F5	5	5	2.3			
T Sex	094802	204	+41	9.50	0.67	0.32468	A2	6:	5:	7.0:			
RW TrA	165066	292	−15	*10.79*	*0.91*	0.37404	A7	4	4	5.5			
RV UMa	132954	75	+63	*9.89*	*1.27*	0.46807	F0	5	4	2.0	−209	−148	1
AI Vel	081044	228	− 5	*6.8*	*0.3*	0.11157	F0	5::	6:	..			5

Remarks to Table IV, II

1. Velocity, Adams and Joy, P. A. S. P., **36**, 139, 1924.
2. Velocity, Wilson, A. J., **35**, 35, 1923.
3. Velocity curve, Kiess, L. O. B., **7**, 146, 1913; Sanford, Mt. W. Contr. 510, 1935.
4. Velocity, Adams, Humason, and Joy, P. A. S. P., **39**, 368, 1927.
5. Light curve very variable (Zagar, B. A. N. 300, 1937; van Hoof, B. A. N. 300, 1937); period considered doubtful Probably not to be regarded as a true cluster type star.
6. Light curve very variable (Balázs and Detre, Abh. d. Astrophys. Obs. Budapest, No. 5, 1938).

TABLE IV, IX

STARS ASSIGNED TO THE BETA CANIS MAJORIS GROUP (DWARF CEPHEIDS)

Star	H. D.	HPv Mag.	Period	Spect.	Remarks	Ref.
δ Cet	16582	4.00	d 0.1556	B2	Form and amplitude of velocity curve, and probably also velocity of center of gravity, variable.	1
					Brightness of star not perceptibly variable.	2
(20 Tau)	23408	3.95	...	B9s	Maia; light not perceptibly variable.	3
(μ Tau)	26912	4.33	...	B3		7
ν Eri	29248	4.06	0.23667	B2s	Radial velocity variable.	4
					Light amplitude $0^m.1$.	5
η Aur	32630	3.23	...	B3	Small light variation suspected.	6, 7
(114 Tau)	35708	4.81	...	B3sk	Velocity first considered variable, but probably constant	8, 9
(σ Ori)	37468	3.76	...	B0, O9s	Velocity range 21 km/sec.	10
β CMa	44743	1.97	0.25714	B1	Variations of amplitude and of line width.	11
					Variation of brightness.	12
(10 Mon)	45546	4.99	...	B3		7
(4 CMa)	46328	4.37	...	B1		7
42 Cam	48879	5.11	0.1385	B3	Radial velocity probably not variable.	13
					Brightness not variable.	14
					Line intensity variable.	15
(15 CMa)	50707	4.69	...	B1, B0s	Velocity considered constant.	16
β UMa	95418	2.34	0.31234	A0n	Lines broad; form and amplitude of velocity curve variable.	17
					Brightness varies by $0^m.02$ in a period of $0^d.3122$.	18
ε UMa	112185	1.61	0.95203	A2s	Radial velocity variable.	19
					Light variable by $0^m.04$ in a period of $0^d.95203$.	20
g UMa	116842	3.82	0.155	A1n	Light variable by $0^m.03$; perhaps only sometimes variable; lines doubled.	21

TABLE IV, IX—*Continued*

Star	H.D.	HPv Mag.	Period	Spect.	Remarks	Ref.
			d			
γ Boo	127762	2.90	0.290309	A3n	Light variable by $0^m.03$ to $0^m.04$.	22
γ UMi	137422	3.08	0.10844	A2n	Velocity curve variable in form and amplitude.	23
					Light variable by $0^m.10$.	24
σ Sco	147165	3.03	0.246834	B1	Velocity curve determined.	25
θ Oph	157056	3.31	0.2862	B2	Velocity curve determined.	26
δ Sct	172748	4.69	0.19374	F4	Velocity curve variable in form and amplitude.	27
					Light curve variable in amplitude;	28
					a secondary period found.	28a
(η Lyr)	180163	4.44	. . .	B3	Not variable in light.	29
					Radial velocity constant.	30
(2 Cyg)	182568	4.82	. . .	B2		7
δ Aql	182640	3.36	0.157	F0n	Velocity curve determined.	31
(8 Cyg)	184171	4.75	. . .	B3, B5s	Radial velocity constant.	30
(ι Aql)	184930	4.14	. . .	B5	No sensible variation in light.	32
					Radial velocity constant.	33
(55 Cyg)	198478	4.78	. . .	cB2	Radial velocity constant.	30, 32
τ Cyg	202444	3.71	0.1425	F0n	Elements approximate.	34
β Cep	205021	3.28	0.190485	Bls	Radial velocity variable.	35
					Velocity curve variable in shape and amplitude; velocity of center of gravity variable.	36
					Period variable.	37
					Light variable by $0^m.05$.	38
(9 Cep)	206165	4.86	. . .	B2p	Light not noticeably variable.	39
12 Lac	214993	5.24	0.193089	Blsk	Amplitude of velocity curve variable between 1 km/sec and 70 km/sec.	40
					Shape of velocity curve, and center of gravity of velocity curve, variable, with long period; spectral lines vary in width.	
					Light variable by $0^m.13$.	41

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2. Güssow and Guthnick, Kl. Veröff. d. Univ. Sternw. Ber.-Bab., No. 8, 1930; star No. 49.
3. Guthnick and Pavel, A. N., **215**, 395, 1922.
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9. Moore, Fourth Catalogue of Spectroscopic Binaries, L. O. B., **18**, 1, 1936.
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11. Meyer, P. A. S. P., **46**, 202, 1934.
12. Güssow and Guthnick, *op. cit.*, star No. 164; Fath, L. O. B., **17**, 116, 1935.
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14. Baker, P. A. S. P., **38**, 95, 1926.
15. Edwards, M. N., **93**, 729, 1933.
16. Moore, *op. cit.*
17. Guthnick and Prager, Veröff. Ber.-Bab., **2**, Part 3, Table I, 1918.
18. Guthnick and Prager, *op. cit.*, p. 59, 1918.
19. Guthnick and Prager, *op. cit.*, Table I, 1918.
20. Guthnick and Prager, *op. cit.*, p. 52, 1918.
21. Guthnick and Prager, *op. cit.*, p. 117, 1918.
22. See Güssow and Guthnick, *op. cit.*, star No. 290.
23. Struve, Pop. Astr., **31**, 90, 1923.
24. Güssow and Guthnick, *op. cit.*, star No. 306.
25. Henroteau, L. O. B., **9**, 176, 1918.
26. Henroteau, D. A. O., **8**, 3, 1922.
27. Colacevich, L. O. B., **17**, 171, 1935.
28. Fath, L. O. B., **17**, 175, 1935.

28a. Sterne, Ap. J., **87**, 133, 1938.

29. Stebbins, Publ. Washburn Obs., **15**, 92, 1928.
30. Moore, *op. cit.*
31. Henroteau, D. A. O., **8**, 59, 1923.

32. Baker, P. A. S. P., 38, 96, 1926.

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34. Paraskevopoulos, Ap. J., 53, 146, 1921.

35. Mendenhall, L. O. B., 14, 133, 1930; *see also* van Arnam, D. A. O., 4, 171, 1928; Duncan and Mitchell, Ap. J., 70, 126, 1929; Struve and Ogrodnikoff, Publ. Amer. Astr. Soc. 7, 105, 1932.

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38. Güssow and Guthnick, *op. cit.*, star No. 441; Güssow, A. N., 229, 197, 1927; *ibid.*, 233, 1, 1928.

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41. Güssow and Guthnick, *op. cit.*, star No. 470; Stebbins, Publ. Washburn Obs., 15, 51, 1928; Fath, Publ. Amer. Astr. Soc., 9, 38, 1938.

CHAPTER V

THE GREAT SEQUENCE, III

THE SEMIREGULAR VARIABLES

All discord, harmony not understood.
Pope

The present chapter deals with a number of stars that have been treated in several different groups by previous writers.[1] Table V, I contains over a hundred and fifty stars, which various authors have classified as RV Tauri stars; μ Cephei stars; stars with periods between 45 and 90 days; UU Herculis type; variables of the intermediate group; stars between Cepheids and RV Tauri stars; stars between RV Tauri and Mira type; stars between Mira and μ Cephei type; and many others, which it is unnecessary to name, for happily it appears to be unnecessary to form so many subdivisions.

35. Types of Semiregular Variables.—The best known group, including more than a quarter of these stars, is the so-called RV Tauri group. But a survey of the literature reveals no unanimity as to what constitutes an RV Tauri star. The criteria given by Gerasimovič[2] are far superior, from the point of view of definition, to the more descriptive definition of Ludendorff:

> "They vary continuously in brightness, the minima being alternately shallow and deep; the difference in brightness between successive minima is variable so that in the course of a few years the shallow and deep minima may interchange. The light curve varies, sometimes resembling that of β Lyrae, sometimes of δ Cephei. Maximum light is slightly variable, and other irregularities often complicate the light variation considerably. From a formal point of view the period may be reckoned as the interval between two successive minima of the same kind, and usually exceeds fifty days."

[1] Ludendorff, Handbuch d. Ap., 6, 1928; Gerasimovič, H.C. 341 and 342, 1929.

[2] H.C. 341, 1929.

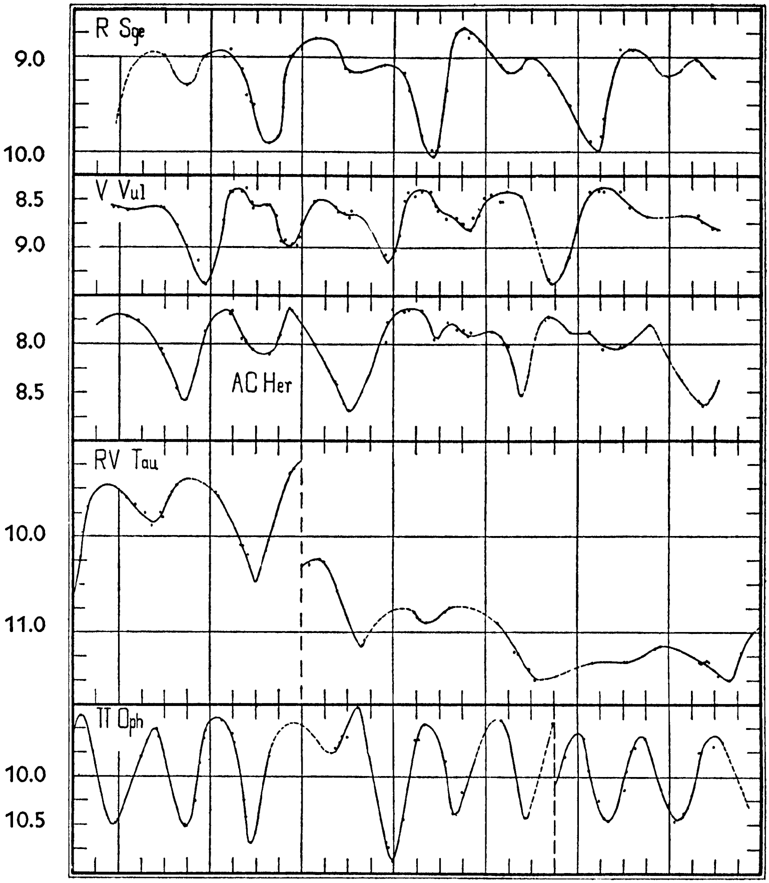

Figure V, 1—Typical "RV Tauri" stars:

R Sagittae	$P=70\overset{d}{.}8$	Spectrum cG7	J.D. 2424600—2424900,
V Vulpeculae	76.0	cG7—cK0	2424600—2424900
AC Herculis	75.2	F8—K4	2424600—2424900
RV Tauri	78.6	K0—M	2424020—2424120, and 2424780—2424980
TT Ophiuchi	61.1	F8p	2424620—2424830, and 2425340—2425430

All observations from Beyer, Astr.Abh., 8C, 1930.

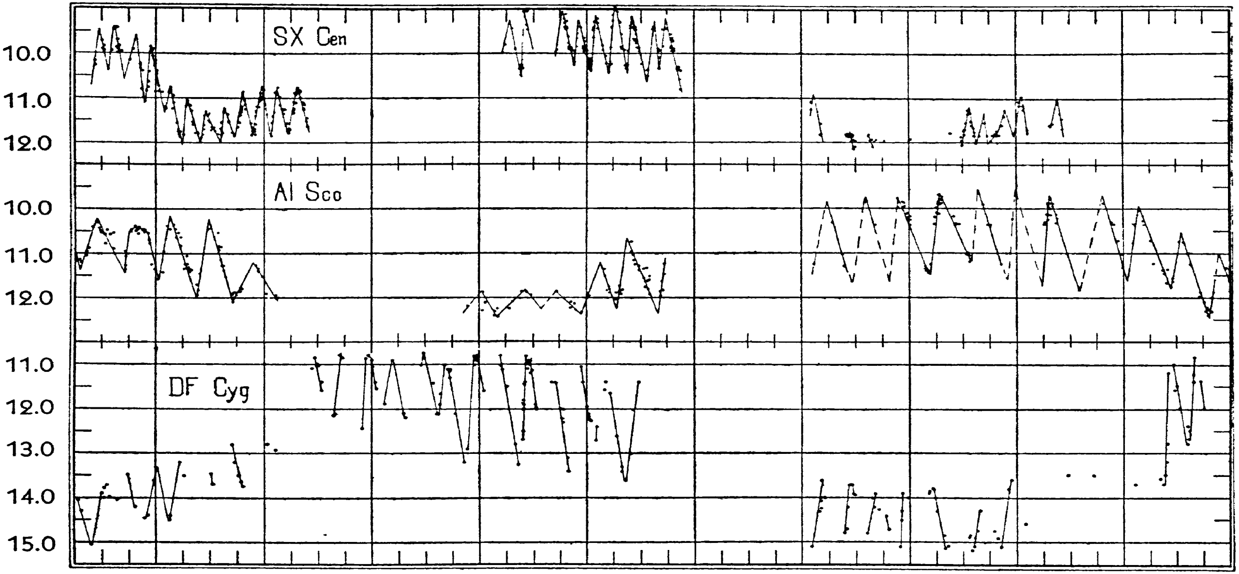

Figure V, 2.—Typical "SX Centauri" stars, as follows:

	d				
SX Centauri	P_1=16.5	P_2=600^d	Spectrum	F5	J.D. 2424525—2425600
AI Scorpii	36	930		K	2424975—2426050
DF Cygni	49.808	782		cG7—cK2	2426175—2427250

Sources of observations: SX Centauri and AI Scorpii, Voûte, Lembang Ann., 2, Part 4D, 1932; DF Cygni, Miss Harwood, H.A., 105, 533, 1937.

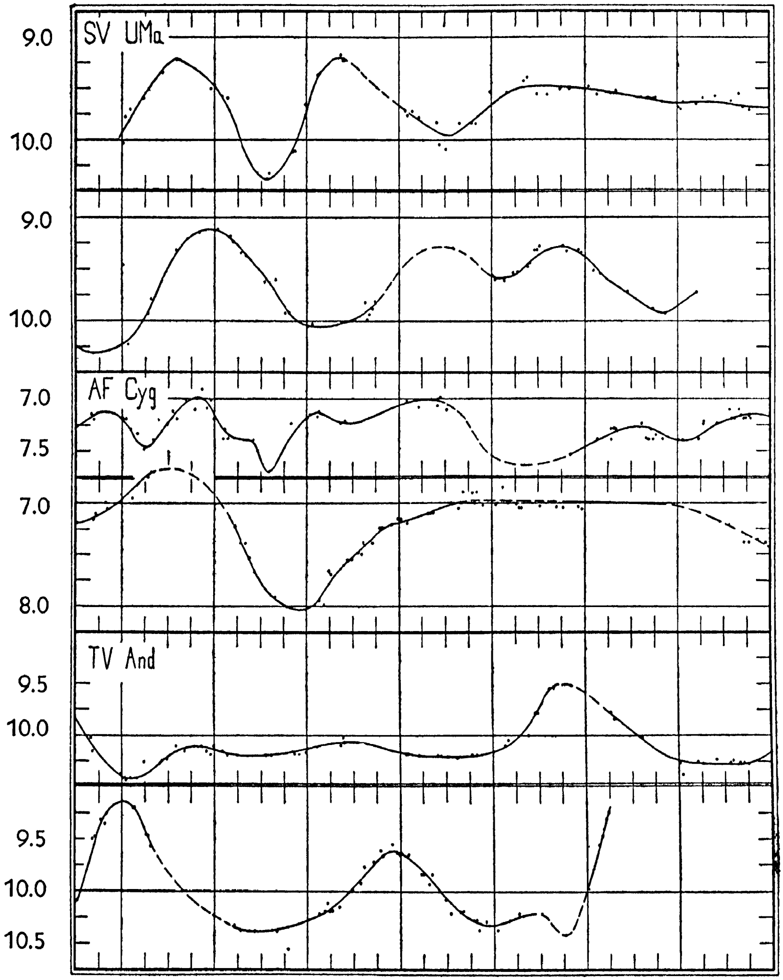

Figure V, 3.—Typical "long-period" semiregular variables:

	d		
SV Ursae Majoris	P=76.3	Spectrum K2	J.D. 2425000—2425300 and 2425400—2425700
AF Cygni	182.4	M4	2424000—2424600
TV Andromedae	114.8	M4	2424000—2424600

All observations from Beyer, Astr.Abh., 8C, 1930.

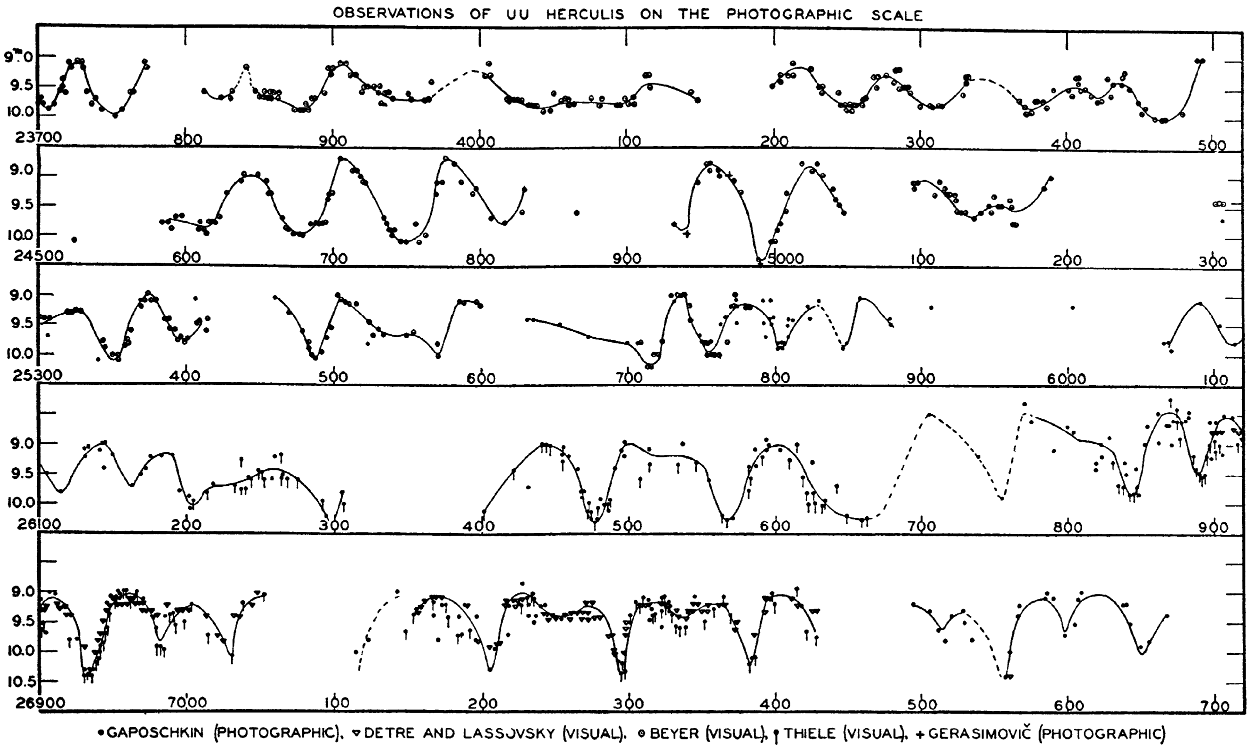

Figure V, 4.—Photographic observations of UU Herculis; taken from S. Gaposchkin, H.B. 903, 1936.

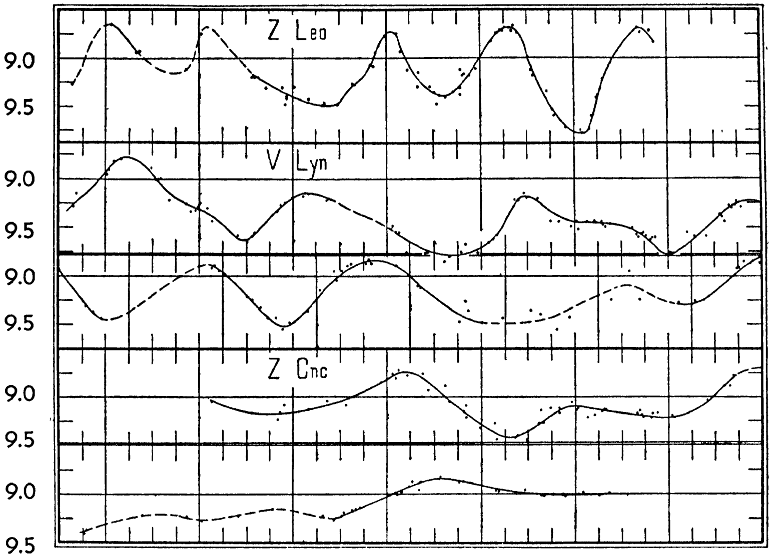

Figure V, 5.—Typical "UU Herculis" stars:

	d	Spectrum Me	J.D. 2424060—2424360
Z Leonis	P=56.8	(M)	2424000—2424300 and
V Lyncis	87.1		2425030—2425330
		M5	2424000—2424300 and
Z Cancri	80		2425500—2425800

All observations are from Beyer, Astr.Abh., 8C, 1930.

There are only seven stars common to the lists of Ludendorff and Gerasimovič (AC Herculis, U Monocerotis, TT Ophiuchi, R Sagittae, R Scuti, RV Tauri, and V Vulpeculae). Among over forty stars that have been assigned to the class by various investigators, only 23 are well enough observed for a definite conclusion that they conform to the criteria of Gerasimovič; he, himself, assigned but twelve stars to the group in 1929, and of these at least DF Cygni must now be classed otherwise. Thus the RV Tauri class is a rather indefinite one, and indeed the prototype, RV Tauri itself, has recently been shown to display a new peculiarity, which was previously not considered a characteristic of the class — it has a secondary variation of long

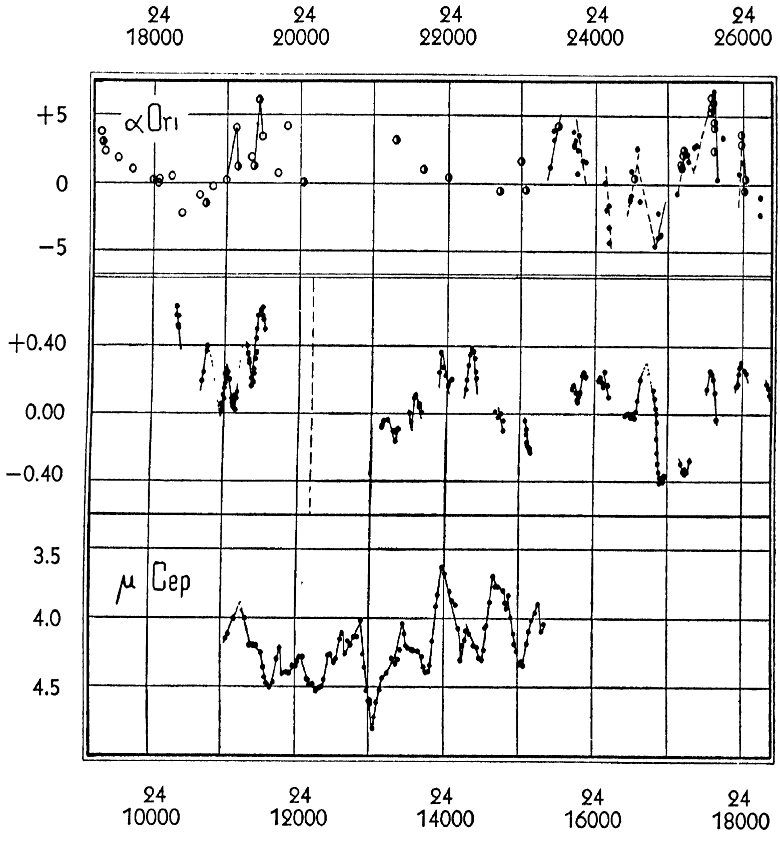

Figure V, 6.—Typical "μ Cephei" stars:

α Orionis: Above, observations of radial velocity (Spencer Jones, M.N., 88, 660, 1928; Sanford, Ap.J., 77, 110, 1933). Dots, crosses, and circles denote respectively, Cape, Lick, and Mount Wilson observations. The curve is empirically drawn.

α Orionis, below: observations of brightness (Stebbins, Publ. Washburn Obs., 15, 177, 1931; Pop.Astr., 21, 5, 1913). Observations before the broken line (selenium photometer) differ in zero point from the later ones (photoelectric photometer). The upper row of abscissae refers to both light curve and velocity curve of α Orionis.

μ Cephei: visual light curve (Plassmann, Himmelswelt, 39, 63, 1929; Zessewitsch, Mirov.Ats.Bul. 22, 1928).

period. The star RV Tauri can therefore no longer be regarded as a member of the RV Tauri class (as defined above), but must be placed with such stars as SX Centauri, and μ Cephei.

Even greater chaos reigns in the definitions of other classes. The μ Cephei class was first formed[3] to include stars of late spectral type with irregular variations, but later μ Cephei itself was shown to have a complex variation with a long and short period, something like SX Centauri; and these properties of the star were tacitly transferred to the class, although the latter contained such objects as ϱ Persei, α Herculis, and α Cassiopeiae, which show no definite regularities, and should be considered among the truly irregular red variables.[4]

As regards the group of stars with periods between 45 and 90 days, there was originally only one reason for treating them as a definite group, intermediate between Cepheids and long-period variables—there were so few of them that their general properties could not be discussed. But there is no physical reason for considering this group of stars as a single entity. On the contrary, as has been shown in the previous chapter, the long-period variables and the Cepheids not only approach one another in length of period, but actually overlap considerably. The fact that the number of stars with periods between 45 and 90 days is not large is only another consequence of the conspicuous minima of frequency of period that occur throughout the Great Sequence—at 1.6 days, at 9 days, at 80 days, and probably also at 700 days. These minima of frequency of period are all accompanied by profound changes in the shapes of the light curves, and it is not surprising that light curves of unusual shape should occur in the interval considered; it is indeed not impossible that all the minima of frequency of period are characterized by unstable light curves (compare, for instance, the light curve of SU Cassiopeiae[5], $P=2^d.14$), which are strikingly different at different maxima; such variability of light curve is of course more difficult to establish for short than for long periods. Therefore it is not impossible that all the stars in the period interval 45-90 days are either to be regarded as Cepheids of long period or long-period variables of short period, and they are so indicated in Table V, I. The existence of such peculiarities as are shown by RV Tauri and SX Centauri is not excluded by this idea: they are characteristic of the minimum of period frequency. For example, some Type b cluster-type variables have a hump on the downward branch—the beginnings of a secondary minimum; a similar phenomenon appears a little before 9 days (S Sagittae); secondary minima are prevalent between 45 and 90 days (RV Tauri stars) and reappear among the long-period variables of longer period (R Centauri, UW Aurigae).

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[3] Handbuch d. Ap., 6, 166, 1928.

[4] See Chapter VI.

[5] Miss Sawyer, H.B. 871, 19, 1929; Robinson, H.A., 90, 46, 1930; see Sections 33, iii, and 34.

The "UU Herculis" type was created by Gerasimovič as a result of his conclusion[6] that this star has several independent periods that operate at different times. But further observation of UU Herculis has thrown much doubt on the reality of these independent periods; for the last seven years the star has behaved as a normal "RV Tauri" star.[7] The UU Herculis type is clearly and unambiguously defined by the possession of several independent periods, but we cannot at present consider that the existence of any members of it has been definitely established; all the stars that have been assigned to it (Z Cancri, Z Leonis, UU Herculis, V Lyncis) vary in such an irregular manner that observations are very difficult, and the observer must be exceptionally careful in drawing conclusions from incomplete data. Continuous observations of these four stars over a number of years would be of the greatest value; all are fairly bright, and well adapted to visual observation with modest equipment.*

From these remarks it follows that classes such as those including stars "Intermediate between RV Tauri and Cepheid types" and "between μ Cephei and long-period variables" have little, if any, meaning, since the limiting groups are themselves ambiguous. Critical discussion of the various classes is not to be interpreted as criticism of describing one star by likening it to another; it is only suggested that the formation of classes and subclasses on the basis of the properties of individual stars is misleading and not to be desired.

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[6] H.B. 857, 862, 1928.

[7] S. Gaposchkin, H.B. 903, 1936.

* The observed variation of AC Andromedae with two independent and simultaneous periods has been referred to the variations of two unresolved stars of comparable brightness (Florja, R.A.J., 14, 1, 1937) and is not a true case of semiregularity.

36. List of Semiregular Variables (Related to the Great Sequence).—As a result of our critical discussion of the classes, we assemble together in Table V, I all stars, periodic and quasi-periodic, that may be considered as related to the Great Sequence. The column of remarks contains the results of a comparative study of the properties of all the stars. The variation of light of each star is characterized in the remarks by two or more descriptive letters, arranged in order of applicability, but not to be regarded as of the nature of classifications.

37. General Properties of the Semiregular Variables.—There is little need to discuss the stars of Table V, I in detail; most of the important facts concerning them are already given in the remarks. The frequency of periods is summarized below (stars of period up to 110 days):

Period	40	41–50	51–60	61–70	71–80	81–90	91–100	101–110
No. of stars	5	7	7	19	23	27	18	5 = 111

Between 111 and 240 days there are 39 stars, mostly of spectral class M. The frequency of spectra is as follows:

Spectrum	F	G	K	M	N	S	R
No. of stars	6	12	16	55	8	1	2 = 100

It is of interest to examine the frequency of spectra separately for stars related to long-period variables, to Cepheid variables (including RV Tauri stars), or to irregular variables, as indicated in the notes to Table V, I. The results are as follows:

Spectrum	F	G	K	M	N	S	R
Long period	0%	0%	10%	62%	62%	100%	50%
Cepheid	85	80	90	18	0	0	50
Irregular	15	20	0	20	38	0	0

The distribution of spectra between the three groups, affiliated (from characteristics of the light curves) with well-defined Great Sequence and irregular groups, indicates that the suggested relationships are probably real. The stars related to the Cepheids resemble Cepheids in spectrum; those related to the long-period variables show also the characteristic late type spectrum; and we may conclude that irregular variability is preferentially associated with late type spectrum, a conclusion borne out by the table of irregular variables given in a later chapter (Table VI, I).

The first table of this chapter obviously displays the large variety in galactic latitude. This is not surprising because the stars related to the Great Sequence are mixtures of at least two classes. The numerical investigation of all stars in the table leads to the following conclusions: among the stars which we associated with the long-period variables there are many of high galactic latitude. Among stars associated with the Cepheids there is a definite group of RV Tauri stars with high galactic latitude. This may recall a similar group among the Cepheids themselves. Finally the irregular stars display no peculiarity.

Group	Mean Gal. Lat.	Number
Long periodic	23	81
Cepheid	19	49
Irregular	22	33

This little table shows that there is no definite distinction between the different groups of stars included in this chapter. It may suggest that having more or less the same distribution in the galactic system the stars like RV Tauri, irregular long-periodic variables, and the rest are more or less of the same luminosity and perhaps also of the same mass. It may be of further interest to mention that the so-called α Orionis stars and UU Herculis stars are located nearly in the same average galactic latitude.

The physical properties of the stars related to the Great Sequence are scarcely known. For the bright red variables like α Orionis and μ Cephei, we have detailed information in regard to radial velocity and parallax. Also, a few variables of RV Tauri type have been investigated in their physical properties. A very important collection of material has been made by Parenago[8]. He undertook to enlarge our knowledge about the physical properties of RV Tauri stars by determining their absolute magnitude in various ways, chiefly with the aid of proper motions. We give a short summary of his results, published in 1934. The average absolute visual magnitude for RV Tauri stars will be about –0.6, which becomes –0.9 because the star W Serpentis, now known to be an eclipsing star, should be removed from the list. In any case, the stars are not brighter than –1.0, much fainter than the Cepheids of corresponding period. On the other hand, the value derived for the RV Tauri stars is not far from that for long-period variables. This fact, that the semiregular variables are in general closer to the long-period variables than to the Cepheids, is not a new one. Parenago in 1933 made a Russell diagram for all available absolute magnitudes of all variables and the result was, that irregular and semiregular stars were situated in the upper corner of his diagram. It is known that the Cepheids are in fact among the most luminous objects of their spectral classes, and may appropriately be called "supergiants."

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[8] R.A.J., 11, 29, 1934; 11, 95, 1934.

TABLE V, I

STARS RELATED TO THE GREAT SEQUENCE

Star	Designation	l	b	M	A	P	Sp.	Remarks	Ref.
					m	d			
SV And	235943	82°	—23°	7.8	6.2	314.0	M7e	Irr.?, Longp.?; P2 = 930^d.	1
TV And	225342	68	—16	8.6	2.2	114.8	M4	Longp.?, RV?, Irr.? Well-observed.	2
U Ant	1030*39*	244	+17	5.7	1.1	168	Nb	Irr.? Little known.	3
UZ Aps	14517*1*	278	—11	12.1	1.8	88.3	—	Longp.? Little known.	4
RU Aqr	2319*17*	25	—68	9.0	1.3	170	M5e	Longp.? Secondary waves; CI=1.0? Conflicting results.	5
TU Aqr	2102*00*	19	—32	*10*	*2.5*	97	—	Longp.?; Very little known.	6
TW Aqr	2058*02*	18	—33	*11*	*1*	79	—	Longp.? Little known.	7
XY Aqr	231*618*	24	—74	9.4	0.7	72.7	G0	Cep? Period is not certain. Few observations.	8
AC Aqr	2111*02*	18	—33	9.5	0.5	67	F8	Eclipsing? Period? Little known.	9
BC Aqr	*222618*	9	—56	*14.6*	*1.6*	88	—	Longp.? Little known.	10
BL Aqr	2109*02*	9	—55	9.5	2.0	85	—	Longp.? Irr.? Little known.	11
BM Aqr	2201*16*	24	—64	10.0	1.0	60	Ma	Irr? Little known.	12
TX Aql	200103	13	—16	10.1	0.6	34.8	—	RV? Cepheid? Well-observed, but with conflicting results.	13
TZ Aql	2023*05*	6	—25	8.5	1.0	90	M6	UU Her? Irr.? Little known.	14
AD Aql	1853*08*	356	— 8	*11.9*	*0.7*	64	—	RV? Cepheid? Eclipsing? Little known.	15
IS Aql	1905*00*	3	— 5	*13.2*	*1.2*	69.6	—	RV? Little known.	16
KK Aql	194314	20	— 8	*10.6*	*1.5*	90.0	—	RV? Period? Little known.	17
LN Aql	193111	16	— 6	*14.5*	*0.9*	65	—	RV? Little known.	18
LU Aql	193415	20	— 6	*10.9*	*1.1*	50	M1	Irr.? Period? Little known.	19
NV Aql	194113	20	— 6	*11.9*	*1.3*	110	—	Longp.? Period? Very little known.	20

TABLE V, I—*Continued*

Star	Designation	l	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
BQ Ara	174146	314	−12	*11.9*	*1.9*	81.1	—	Longp.? Little known.	21
TU Aur	062845	136	+16	7.7	1.4	75	Mb	Irr.? Longp.? Period? Little known.	22
UU Aur	062938	155	+12	5.1	1.7	235	N3	μ Cephei? P2 = 3000^d; Irr.? Well-observed with conflicting results.	23
UX Aur	050749	128	+ 7	8.0	0.8	90	M2	Irr.? Longp.? Little known.	24
UZ Aur	050839	136	+ 2	7.7	1.6	66	Ma	Irr.? Longp.? Little known.	25
AG Aur	061947	135	+17	8.7	2.3	98.3	G–M	Longp.? RV? Well-observed. Radial velocity = +196 km/sec.	26
RX Boo	141926	0	+64	7.0	2.2	78	M6–M7	Longp.? Second waves, P2 = 500^d; Little known.	27
RS Cam	083679	102	+34	8.1	1.4	166	Mb	Irr.? Longp.? δ Cephei? RV?; P2=1000^d. Well-observed.	28
RV Cam	042257	115	+ 7	7.9	1.1	107.1	M3	Longp.? Irr.? Little known.	30
Z Cnc	081615	177	+29	8.5	1.3	80	M5	UU Her? Irr.? RV? P2=114^d, P3=166^d, P4=351^d? Well-observed but without a united discussion and results.	31
RS Cnc	090431	163	+43	5.3	1.5	239	M6	RV? Well-observed.	32
RT Cnc	085211	185	+33	7.3	1.3	100	Ma	Irr.? Longp.? Period? Little known.	33
T CVn	122532	115	+87	8.6	4.2	283.6	M5	Irr.? Longp.? Period? Little known.	34
Z CMi	072903	190	+ 6	*14.0*	*1.2*	140	—	Irr.? Very little known.	35
SZ CMi	073104	182	+12	*12.4*	*1.0*	125	—	Irr.? Very little known.	36
RX Cap	200913	357	−24	10.9	1.3	*67.7*	—	RV; no discrepancies in observational results.	37
GK Car	*110957*	*257*	+ 4	*12.5*	*1.5?*	*55.6*		RV? Little known.	38

Table V, I—*Continued*

Star	Designation	l	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
VY Cas	004562	91	+ 1	9.0	1.2	83.8	M4–M5	Longp. :R UMi? RV? Period? Well-observed.	39
α Cas	003455	88	− 7	2.1	0.5	26	G8	Irr.? P2=360^d? Well-observed.	40
δ Cas	011959	93	− 3	3.0	0.1	759	A3n	Irr.? Eclipsing? Little known; probably not related to the Great Sequence.	41
ϱ Cas	234956	82	− 7	4.4	0.7	1100	cG5	Irr.? α Orionis? Well-observed, but with conflicting results.	42
T Cen	1336*33*	283	+27	5.6	3.4	90.8	K8e–M3, L (F)	Well-observed.	43
RU Cen	1331*55*	263	+17	8.8	1.5	64.7	G2–K2	Eclipsing? Cepheid? Little known.	44
SX Cen	1215*48*	267	+12	8.6	3.5	16.5	F5	Prototype of the class (with two periods) P2=600^d.	45
IM Cen	1351*55*	293	0	*13.7*	*1.2*	49.5	—	Period? Cepheid? Little known.	46
KQ Cen	1417*63*	280	− 3	12.0	1.5	136	—	Irr.? Longp.? P2=159? Little known.	47
RU Cep	010884	93	+23	8.3	1.0	117.0	K8	Longp.? RV? Period? Well-observed.	48
SS Cep	033680	104	+10	6.7	1.1	100.4	Mb	Longp. :R UMi? Period? Little known.	49
TZ Cep	001973	87	+12	9.3	2.4	83.1	M0	Longp. CI=1.3; well-observed.	50
μ Cep	214058	68	+ 4	4.0	0.8	750	M2	Prototype of a class, which is more or less identical with the α Orionis class.	52
T Cet	001620	45	−78	5.2	0.8	158.8	M3	Irr.? Longp.? Little known.	53
SY Cir	1355*69*	278	− 9	*12.2*	*2.8*	46.4	—	Eclipsing? Little known.	54
W CrA	1758*39*	321	−11	*10.0*	*1.0*	109	R5	Longp. :R UMi? Well-observed.	55
RX CrA	1819*44*	318	−18	*10.5*	)4.5	149	M3e	Longp.? Little known.	56
CT CrA	1846*39*	308	−17	*14.2*	*1.4*	64	—	Longp.?	57

TABLE V, I—*Continued*

Star	Designation	1	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
RR CrB	153738	30	+58	7.2	1.2	56.8	Mb	Longp. :R UMi? Well-observed; Period?	58
W Cyg	213244	60	− 5	5.1	1.9	130.6	M4	Prototype of a class, which is identical with R UMi; well-observed.	59
RR Cyg	204244	44	− 6	*12.9*	*0.9*	217	M? (N)	Longp. :R UMi? Period? Little known.	60
TT Cyg	193732	34	+ 4	7.3	1.6	120	N	Longp.? Little known.	61
TZ Cyg	191350	48	+15	9.5	2.0	90	M7	Longp.? Little known.	62
AC Cyg	200949	53	+ 5	*9.2*	*0.8*	118.3	Mc	μ Cep? Irr.? Little known.	63
AD Cyg	202732a	40	− 3	8.3	1.6	72.8	S	Longp.? Period? Few observations with conflicting results.	64
AF Cyg	192745	46	+12	6.4	2.0	182.4	M4	Irr.? Longp.? Period? Well-observed. Rad. V= −23.7— + 7.8 km/sec.	65
AH Cyg	195739	43	+ 3	10.0	1.6	99.5	—	Longp.? Irr.? Period? Little known.	66
AV Cyg	191629	30	+ 7	10.4	1.2	87.4	K5	RV; well-observed.	67
DF Cyg	194542	36	+ 7	*10.7*	*4.7*	49.9	cG7–cK2	SX Cen, RV?? P2=790^d; well-observed.	68
V360 Cyg	210630	44	−12	10.7	0.7	64.0	—	δ Cep? RV? well-observed.	69
TU Del	202212	22	−10	*12*	*2*	90	—	Longp.? Little known.	70
SS Dra	122169	95	+50	8.6	1.4	48.2	Mb	RV? Little known.	71
SZ Dra	190965	64	+26	8.0	0.6	124	M6	Longp.? Little known.	72
TX Dra	163360	60	+42	6.8	1.3	76.6	M5	SX Cen? Irr.? well-observed.	73
UU Dra	202574	75	+17	8.7	1.6	120	M6	SX Cen? P2=960^d; longp.?	74
UV Dra	121269	62	+55	8.8	0.6	77.4	M4	Irr.? Little known.	75
RW Eri	041705	167	−34	*10.2*	*1.5*	91.4	—	RV? Little known.	76
T For	032528	191	+54	8.5	1.2	93.3	M2	Longp.? Little known.	77

TABLE V, I—*Continued*

Star	Designation	1	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
SS Gem	060222	155	+ 3	8.6	0.7	89.3	G0–K0	RV? δ Cep? well-observed.	78
SU Gem	060727	153	+ 3	10.3	1.9	25	K6	SX Cen? P2=716^d; well-observed.	79
X Her	155947	40	+47	5.8	1.4	100	Mc	μ Cep? P2=400^d? Well-observed but with conflicting results.	80
UU Her	163238	27	+40	8.3	1.0	90	cF8	Prototype of a class, which has probably no reality. Well-observed.	81
WX Her	172234	27	+31	*12.4*	*4.3*	77.2	—	Longp.? Little known.	82
AC Her	182621	17	+15	7.2	1.8	75.2	F8–K4	RV? well-observed.	83
CP Her	184224	21	+10	*14*	*1*	30	—	Irr.? Very little known.	84
CX Her	170627	17	+32	*9.5*	*1.0*	90		RV? Very little known.	85
DE Her	180220a	15	+17	*10.8*	*1.7*	151.6	—	RV? Little known.	86
DM Her	173334	27	+28	11.8	0.4	73	—	Irr.? Little known.	87
α Her	171014	2	+26	3.1	0.8	120^d	M5	α Ori? P2=2250? Little known.	88
g Her	162542	33	+43	4.4	1.2	40	Mb	Irr.? well-observed.	89
V Hya	104620	233	+30	6.0	6.5	527.4	N6	Longp.? α Ori? well-observed; P2=6500.	90
Y Hya	094622	223	+24	6.5	1.5	80	N3p	Irr.? Little known.	91
RU Hyi	012082	268	—42	*14.8*	*1.4*	157	—	RV? Little known.	92
RV Lac	224049	70	—10	9.5	1.9	137	(K)	Irr.? Very little known.	93
XY Lac	221452	69	— 4	*12.7*	*1.0*	78	—	Longp.? RV? Little known.	94
AD Lac	222151	68	+ 6	*13*	*1.0*	145	—	Irr.? Very little known.	95
Z Leo	094627	170	+50	8.6	1.4	56.8	Me	Irr.? δ Cep? RV? well-observed.	96
RU Leo	104724	175	+60	10.3	1.7	165	—	Irr.? Period? Well-observed.	97

TABLE V, I—*Continued*

Star	Designation	l	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
SY Leo	104700	22	+50	*11.4*	*1.5*	85	—	Irr.? Period? Little known.	98
U LMi	094836	157	+54	9.8	2.2	280	—	Longp.? Little known.	99
W LMi	103926	176	+63	*11*	*1.5*	87.5	—	Longp.? Very little known.	100
S Lep	060124	198	−20	6.0	2.0	96	Me	Longp.? Little known.	101
U Lup	*155429*	314	+16	10.8	2.4	87	G0	SX Cen? Little known.	102
V Lyn	062061	120	+23	8.6	1.2	87.1	(K5)	UU Her? Well-observed but with conflicting results.	103
R Lyr	185343	40	+18	4.0	0.5	50	M5	Period? Irr.?	104
AF Lyr	*151246*	*27*	*+ 7*	*11.9*	*1.0*	50	—	Irr.? Very little known. Period?	105
DP Lyr	185635	35	+12	*11.5*	*1.5*	90	—	Longp.? Very little known. Period?	106
EG Lyr	190738b	37	+ 2	*11.5*	*1.5*	116	—	Irr.? Little known. Period?	107
U Mon	061702	192	+ 5	5.6	1.7	92.3	G5–K2	δ Cep? RV? Well-observed.	108
SW Mon	062105	173	− 3	9.1	1.5	110	M2	Longp.? Little known.	109
AX Mus	*134168*	*275*	*− 6*	*12.5*	*3.5*	99	—	Longp.? Little known, Period?	110
TT Oph	164403	349	+47	8.8	2.2	61.1	F8p	δ Cep? RV? Well-observed.	111
TX Oph	165905	353	+25	*9.8*	*2.3*	136.2	M0	RV? Rad. Vel. =−160 km/sec, P?	112
UZ Oph	172903	356	+22	9.5	2.5	87.4	F8–K5	δ Cep? RV? Well-observed.	113
DQ Oph	165129b	316	+11	*13.9*	*2.1*	35	—	Irr.? Little known.	114
GQ Oph	165829b	325	+ 8	*14.4*	2.2	90	—	Longp.? Period? Little known.	115
HU Oph	170129a	322	+ 7	*15.5*	*)1.0*	77	—	Longp.? Little known.	116
V371 Oph	165801	346	+24	*13.0*	*2.5*	68	—	Longp.? Period? Little known.	117
W Ori	050001	165	−20	5.9	1.8	200	N5	μ Cep? P2=2000^d? Well-observed.	118
YY Ori	*052906*	185	− 5	*11.8*	*1.0*	140	—	Longp.? Little known.	119

TABLE V, I—*Continued*

Star	Designation	l	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
CX Ori	060813	164	− 2	*13.0*	*1.8*	80	—	Irr.? Little known.	120
α Ori	054907	168	− 8	0.1	1.2	2070	M2	Prototype of a class; P2=? Well-observed.	121
TW Peg	215927	56	−24	6.5	2.7	90	M6	μ Cep? P2=936. Well-observed.	122
AF Peg	224617	55	−36	8.9	1.0	52.4	—	Longp.? Irr.? Little known.	123
BU Peg	213223	43	−22	*12.3*	*0.6*	78.8	—	RV?? Very little known.	124
SW Per	040441	125	− 7	8.2	1.6	83.6	M4	Longp.? RV? Well-observed?	125
TT Per	014453	100	− 7	8.0	1.2	91.5	M5	Irr.? RV? Well-observed but without conclusions.	126
TX Per	024136	113	−20	9.5	2.8	77	Mp	Irr.? RV? Well-observed but with conflicting results.	127
UZ Per	031331	124	−20	7.8	1.2	90	M4	μ Cep? P2=920^d, P3=5000^d. Well-observed.	128
AF Per	033536	124	−14	*9.4*	*1.3*	88.8	M2	Longp.? Little known.	129
V Pyx	084934	224	+ 8	8.4	2.6	70	K2	Longp. :R UMi? Well-observed but with conflicting results. Period?	130
T Ret	035855	231	−45	*11.4*	*1.8*	56	—	Longp.? Little known.	131
R Sge	200916	25	−11	8.6	1.8	70.8	cG7	RV? Well-observed.	132
V Sge	201520	27	− 6	9.5	3.7	17	Ob	Does not belong to this class at all; periods: 17^d and 530^d are incorrect estimates. The star is a Nova.	133
X Sge	200020	28	− 8	8.7	1.0	196	N6	Longp.? Irr.? Well-observed but with conflicting results.	134

TABLE V, I—*Continued*

Star	Designation	l	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
SU Sgr	185722	341	−13	8.3	0.2	88	M7	Longp.? Period? Little known.	135
AL Sgr	191117	0	−14	*11.4*	*3.1*	81.5	—	Longp.? Little known.	136
AM Sgr	191632	341	−44	*10.3*	*3.7*	95	—	RV? Longp.? Little known.	137
AR Sgr	185323	341	−15	*9.5*	*2.0*	88.9	G	δ Cep? RV? Period? Well-observed but with conflicting results.	138
CE Sgr	184736	328	−18	*14*	]2.0	90.4	—	Longp.? Little known.	139
CG Sgr	185335	329	−18	*14*	*0.4*	64.1	—	δ Cep? Little known.	140
DL Sgr	192932	343	−50	*13.0*	*4.0*	80.4	—	Longp.? Irr.? Little known.	141
V514 Sgr	181825	335	− 7	*15.4*	*1.0*	66	—	Cep? Little known.	142
SX Sco	174035	321	− 3	*9.6*	*1.5*	128	N6	Irr.? Little known.	143
AI Sco	174933	325	− 4	*10.4*	2.3	36	K	Prototype of the class which is called SX Cen. Well-observed; P2=930^d.	144
DU Sco	164430	317	+10	*12.2*	*1.3*	70	—	Irr.? Period? Little known.	145
EQ Sco	164830	317	+10	*14.7*	*1.7*	90	—	Longp.? Period? Little known.	146
IU Sco	165530c	320	+ 7	*14.8*	*1.5*	69	—	Cepheid? Little known.	147
MT Sco	172841	316	− 6	*14.4*	)*1.7*	104.4	—	Longp.? Little known.	148
OZ Sco	173743	315	− 8	*13.8*	2.6	95	—	Longp.? Little known.	149
V352 Sco	174540	318	− 8	*15.0*	)*1.5*	97.5	—	Longp.? Little known.	150
BZ Sct	185205	356	− 2	*13.0*	*1.0*	80	—	RV? Little known.	151
Z Ser	151002	337	+40	9.4	1.0	87.6	—	RV? Irr.? Little known.	152
AB Ser	171613	340	+ 7	*10.5*	)*1.5*	93	—	Longp.? Little known.	153
RV Tau	044126	136	−15	9.4	3.1	78.6	K0–M	Prototype of a class. Well-observed but without united conclusions. P2=1360^d.	154

Table V, I—*Continued*

Star	Designation	l	b	M	A	P	Sp.	Remarks	Ref.
					m	*d*			
WW Tau	035529	133	−17	9.6	1.6	116	K7	RV? Cepheid? Well-observed.	155
W Tri	023534	115	−22	8.2	0.8	148	M5	Longp.? Irr.? Period? Little known.	156
DV TrA	163064	295	−11	*13.2*	*2.9*	34.3	—	RV? Cepheid? Little known.	157
Z UMa	115158	104	+57	8.4	1.8	198	M6e	RV? Well-observed; Period?	158
RX UMa	090567	115	+38	10.0	2.5	64	—	Longp.? Irr.? Well-observed. Period?	159
RZ UMa	080165	115	+34	8.8	1.4	136.4	M7	UU Her? Period? Well-observed but with conflicting results.	160
ST UMa	112245	128	+66	6.5	0.8	81	Mb	Irr.? μ Cephei? Well-observed but with conflicting results.	161
SV UMa	104055	120	+55	8.8	1.2	76.3	K2	δ Cephei? RV? Irr.? Rad. Vel. = −95 km/sec. Well-observed but without definite conclusions.	162
TZ UMa	120458	95	+50	9.1	1.0	178.7	Ma	Longp.? Little known.	163
UV UMa	125153	85	+65	10.4	1.1	51	—	RV? Cepheid? Little known.	164
V UMi	133674	84	+43	7.1	1.8	70.5	M4	Longp.? Period? Well-observed but with conflicting results.	165
RU Vel	104952	252	+ 7	*10.7*	*4.6*	63.0	M3e	Longp.? Little known.	166
S Vul	194427	32	0	*10.2*	*0.5*	67.8	K–M2	Cepheid. Longp.? RV? Well-observed but without definite conclusions.	167
V Vul	203226	58	−28	8.2	1.8	76.0	cG7–cK0	δ Cep? RV? Well-observed but with conflicting results.	168
RT Vul	190722	21	+ 6	7.5	1.5	62	A0	Eclipsing? Little known.	169

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5	RU	Aqr:	Ryves, M. N., 92, 134, 1932; Gerasimovič, H. B. 848, 1927.
6	TU	Aqr:	Esch, quoted in G. u. L., II, **1**, 33, 1934.
7	TW	Aqr:	Zessewitsch, Mirov. Bul., 21, 1928.
8	XY	Aqr:	Gerasimovič, H. B. 848, 1927.
9	AC	Aqr:	Parenago, N. N. V. S., **3**, 117, 1931.
10	BC	Aqr:	Hughes, H. B. 883, 1931.
11	BL	Aqr:	Florja, N. N. V. S., **4**, 24, 1932.
12	BM	Aqr:	Florja, N. N. V. S., **4**, 24, 1932.
13	TX	Aql:	Zinner, Erg. A. N., **4**, 3, 1922; Beyer, A. N., **234**, 474, 1929.
14	TZ	Aql:	Gerasimovič, H. B., 869, 1929.
15	AD	Aql:	Zessewitsch, Mirov. Bul., 21, 1928.
16	IS	Aql:	Harwood, H. B. 880, 1931.
17	KK	Aql:	Plaut, A. N., **244**, 289, 1932.
18	LN	Aql:	Hoffleit, H. B. 887, 1932.
19	LU	Aql:	Hoffleit, H. B. 887, 1932.
20	NV	Aql:	Hoffleit, H. B. 887, 1932.
21	BQ	Aql:	Boyd, H. A., 90, 184, 1934.
22	TU	Aur:	Beyer, Erg. A. N., **8**, 69, 1930.
23	UU	Aur:	Kukarkin, Bul. Obs. Corp., 7, 1926; Tchernov, N. N. V. S., **3**, No. 25, 1932.
24	UX	Aur:	Gerasimovič, H. B. 869, 1929.
25	UZ	Aur:	See G. u. L., II, **1**, 111, 1934.
26	AG	Aur:	Merola, A. N., **231**, 247, 1927; unpublished Harvard photographic observations.
27	RX	Boo:	Lause, A. N., **241**, 23, 1930; Bul. A. F. O. E. V., **1**, 159, 1932.
28	RS	Cam:	Martin and Plummer, M. N., **76**, 612, 1916; M. N., **77**, 118, 1916; Hassenstein, Pots. Publ., **87**, 6, 1932.
30	RV	Cam:	Zacharov, A. N., **222**, 159, 1924.
31	Z	Cnc:	Gerasimovič, H. B. 862, 1928; Ahnert, A. N., 5776.
32	RS	Cnc:	Seliwanow, A. N., 219, 343, 1923; N. N. V. S., **4**, 5, 1932.
33	RT	Cnc:	See Prager, G. u. L., II, **1**, 148, 1934.
34	T	CVn:	See Prager, G. u. L., II, **1**, 153, 1934.
35	Z	CMi:	Hoffmeister, A. N., **238**, 35, 1929.
36	SZ	CMi:	Hoffmeister, A. N., **238**, 38, 1929; Kukarkin, N. N. V. S., **3**, p. 18, 1930.
37	RX	Cap:	Parenago, N. N. V. S., **3**, 33, 1932.
38	GK	Car:	Hertzsprung, B. A. N. 201, 1930.
39	VY	Cas:	See Prager, G. u. L., II, **1**, 225, 1934.
40	α	Cas:	Grouiller and Bloch, Lyons Bul., **5**, 76, 1923.
41	δ	Cas:	See Prager, Kat. und. Eph., 1936.
42	ϱ	Cas:	Okounev, A. N., **221**, 225, 1923; Guthnick and Hügeler, A. N., **210**, 351, 1919; See Prager, G. u. L., II, **1**, 232, 1934.
43	T	Cen:	Morse, H. C. 358, 1931; Merrill, Ap. J., **58**, 215, 1923.
44	RU	Cen:	Hertzsprung, B. A. N., **4**, 161, 1928; Shapley and Payne, H. B. 872, 1930; unpublished Harvard photographic observations; Voûte, Lembang Ann., **2**, D63, 1932.

45	SX	Cen:	Voûte, Lembang Ann., **2**, D53, 1932; O'Connell, H. B. 893, 1933.
46	IM	Cen:	Hoffleit, H. B. 874, 1930.
47	KQ	Cen:	Swope, H. B. 883, 1931.
48	RU	Cep:	Hassenstein, Pots. Publ., **83**, 17, 1926; **87**, 23, 1932.
49	SS	Cep:	Gerasimovič: H. B. 869, 1929; Hassenstein, Pots. Publ., **87**, 34, 1932.
50	TZ	Cep:	Hassenstein, A. N., **250**, 265, 1933; Schneller, Veröff, Ber.-Bab., **8**, 26, 1931.
52	μ	Cep:	Zessewitsch, N. N. V. S., **1**, No. 2, 1928; M. N., **90**, 442, 1930.
53	T	Cet:	Lacchini, A. N., **229**, 282, 1925; A. N. **248**, 251, 1933.
54	SY	Cir:	Swope, H. B. 883, 1931.
55	W	CrA:	Unpublished Harvard photographic observations.
56	RX	CrA:	Hartwig, A. N., **212**, 368, 1920.
57	CT	CrA:	van Gent, B. A. N., **7**, 32, 1933.
58	RR	CrB:	Loreta, Bul. A. F. O. E. V., **1**, 15, 1932; Jacchia, Bologna Publ., **2**, 231, 1933.
59	W	Cyg:	Evans, H. B. 899, 1935.
60	RR	Cyg:	Rügemer, A. N., **255**, 176, 1935.
61	TT	Cyg:	Lause, A. N., **238**, 350, 1930.
62	TZ	Cyg:	See Prager, G. u. L., II, **2**, 19, 1926.
63	AC	Cyg:	Zessewitsch, A. N., **235**, 181, 1928.
64	AD	Cyg:	See Prager, G. u. L., II, **2**, 27, 1936.
65	AF	Cyg:	O'Connell, H. B. 888, 1932.
66	AH	Cyg:	Enebo, Dombas, **11**, 19.
67	AV	Cyg:	Enebo, A. N., **217**, 440, 1922; **231**, 12, 1927.
68	DF	Cyg:	Miss Harwood, H. A., **105**, No. 28, 1937.
69	V360	Cyg:	Parenago, N. N. V. S., **4**, 358, 1934.
70	TU	Del:	Hoffmeister, A. N., **242**, 139, 1931.
71	SS	Dra:	Luizet, Journ. Obs., **2**, 13, 1917.
72	SZ	Dra:	Jost, A. N., **249**, 343, 1933.
73	TX	Dra:	Loreta, Bul. A. F. O. E. V., **2**, 99, 1933.
74	UU	Dra:	Hassenstein, Pots. Publ., **87**, 44, 1932.
75	UV	Dra:	Beyer, Erg. A. N., **8**, C40, 1930.
76	RW	Eri:	Hufnagel, H. B. 873, 1930.
77	T	For:	Gerasimovič, H. B. 857, 1928.
78	SS	Gem:	Gerasimovič, H. B. 846, 1927.
79	SU	Gem:	Nabokov, A. N., **230**, 233, 1927.
80	X	Her:	Ryves, M. N., **84**, 171, 1924; Sewerny, N. N. V. S., **3**, 87, 1931; Jacchia, Bologna Publ., **2**, 238, 1933.
81	UU	Her:	S. Gaposchkin, H. B. 903, 1936.
82	WX	Her:	Parenago, N. N. V. S., **4**, 304, 1934.
83	AC	Her:	Waterfield, H. B. 845, 1927; Zacharov, A. N., **221**, 136, 1923; Tashkent Publ., **1**, 66, 1928; Sanford, Ap. J., **73**, 364, 1931.
84	CP	Her:	Hoffmeister, A. N., **236**, 239, 1929.
85	CX	Her:	Hoffmeister, A. N., **240**, 195, 1930.
86	DE	Her:	Beyer, A. N., **262**, 264, 1937; Kanda, A. N., **254**, 279, 1935.
87	DM	Her:	Blazko, N. N. V. S., **4**, 85, 1933.
88	α	Her:	See Prager, G. u. L., II, **2**, 152, 1936.
89	g	Her:	Kopal, A. N., **257**, 11, 1935; Merrill, Ap. J., **58**, 215, 1923.
90	V	Hya:	Loreta, Lyons Bul., **12**, 162, 1930; Jacchia, Bologna Publ., **2**, 238, 1933; Campbell, H. C. 353, 1930; Sanford, Ap. J., **82**, 209, 1935.
91	Y	Hya:	Loreta, B. Z., **16**, Nos. 8, 9, 27, 1934.
92	RU	Hyi:	Hughes, H. A. **90**, No. 4, 1934.
93	RV	Lac:	Martinoff, N. N. V. S., **1**, 5, 1929.
94	XY	Lac:	Parenago, N. N. V. S., **4**, 316, 1934.
95	AD	Lac:	Hoffmeister, A. N., **230**, 420, 1927.
96	Z	Leo:	Gerasimovič, H. B. 849, 1927; S. Gaposchkin, H. B. 896, 1934.

97	RU	Leo:	S. Gaposchkin, H. B. 896, 1934; Beyer, Erg. A. N., **8**, C66, 1930.
98	SY	Leo:	Beljawski, A. N., **229**, 458, 1927.
99	U	LMi:	See Prager, G. u. L., II, 2, 198, 1936.
100	W	LMi:	See Prager, G. u. L., II, **2**, 198, 1936.
101	S	Lep:	Loreta, B. Z., **16**, Nos. 12, 21, 1934.
102	U	Lup:	O'Connell, H. B. 893, 1933.
103	V	Lyn:	Ludendorff, A. N., **214**, 80, 1921.
104	R	Lyr:	Okounev, A. N., **228**, 153, 1926.
105	AF	Lyr:	Hoffmeister, A. N., **233**, 33, 1928.
106	DP	Lyr:	Zverev, N. N. V. S., **4**, 356, 1934.
107	EG	Lyr:	Zverev, N. N. V. S., **4**, 356, 1934; Ibid. **5**, 107, 1937.
108	U	Mon:	See Prager, G. u. L., II, **2**, 251, 1936.
109	SW	Mon:	Esch, B. Z., 67, 1921.
110	AX	Mus:	Swope, A. N., **244**, 85, 1931.
111	TT	Oph:	See Prager, G. u. L., II, **2**, 293, 1936.
112	TX	Oph:	Gerasimovič, H. B. 847, 1927.
113	UZ	Oph:	Leiner, A. N., **233**, 75, 1929.
114	DQ	Oph:	Swope, H. B. 857, 1928.
115	GQ	Oph:	Swope, H. B. 857, 1928.
116	HU	Oph:	Swope, H. B. 857, 1928.
117	V371	Oph:	See Prager, G. u. L. II, **2**, 345, 1936.
118	W	Ori:	H. A., **55**, 132, 1909; O'Connell, H. B. 893, 1933; Zverev, Sternb. S. A. I., **8**, 1, 1936; unpublished Harvard photographic observations.
119	YY	Ori:	Brun, Pub. Lyons I, fasc. 12, 1935.
120	CX	Ori:	Hoffmeister, A. N., **238**, 23, 1929.
121	α	Ori:	Kukarkin, N. N. V. S., **3**, 67, 1931.
122	TW	Peg:	O'Connell, H. B. 893, 1933.
123	AF	Peg:	Enebo, Dombas, **11**, 29.
124	BU	Peg:	Hughes, H. A., 90, **4**, 167, 1934.
125	SW	Per:	Beyer, Astr. Ab., A. N., **8**, 3, 1930; Gerasimovič, H. C. 338, 1929.
126	TT	Per:	Beyer, Astr. Ab., A. N., **8**, 3, 1930; Gerasimovič, H. B. 869, 1929.
127	TX	Per:	Enebo, A. N., **231**, 14, 1927; Lause, A. N., **231**, 46, 1927.
128	UZ	Per:	Gerasimovič, H. B. 864, 1929; O'Connell, H. B. 893, 1933; Zessewitsch, Len. Bul. **2**, 2, 1933.
129	AF	Per:	Beyer, B. Z. 1932, No. 3.
130	V	Pyx:	H. B. 868, 1929; Jordan, H. B. 765, 1922.
131	T	Ret:	Gerasimovič, H. B. 853, 1927.
132	R	Sge:	Gerasimovič, H. C. 340, 1929; and many others.
133	V	Sge:	Jacchia, Pub. Bol. **2**, No. 7, 1931.
134	X	Sge:	Zessewitsch, Len. Bul. 2, 1933; Lause, A. N., **245**, 376, 1932.
135	SU	Sgr:	Payne, H. B. 861, 1928; Parenago, N. N. V. S., **3**, 116, 1931.
136	AL	Sgr:	Payne, H. B. 861, 1928; Parenago, N. N. V. S., **3**, 103, 1931.
137	AM	Sgr:	Payne, H. B. 861, 1928.
138	AR	Sgr:	Zessewitsch, A. N., **231**, 367, 1927.
139	CE	Sgr:	Bailey, H. B. 803, 1924.
140	CG	Sgr:	Gerasimovič, H. B. 846, 1927.
141	DL	Sgr:	Payne, H. B. 861, 1928.
142	V514	Sgr:	Hoffleit, H. A., **90**, 187, 1935.
143	SX	Sco:	ten Bruggencate, Ann. Bosscha Obs., **2**, 2, 1928.
144	AI	Sco:	Voûte, Ann. Bosscha Obs., **2**, 3, 1932; Gerasimovič, H. B. 864, 1929.
145	DU	Sco:	Swope, H. B. 857, 1928.
146	EQ	Sco:	Swope, H. B. 857, 1928.
147	IU	Sco:	Swope, H. B. 866, 1929.
148	MT	Sco:	Boyd, H. A., **90**, 182, 1934.
149	OZ	Sco:	Boyd, H. A., **90**, 183, 1935.
150	V352	Sco:	Boyd, H. A., **90**, 184, 1935.

151	BZ	Sct:	Harwood, H. B. 880, 1930.
152	Z	Ser:	Zacharof, B. Z. 1928, No. 29.
153	AB	Ser:	Hoffmeister, A. N., **240**, 195, 1930.
154	RV	Tau:	Zessewitsch, Len. Bul., **2**, 2, 1933.
155	WW	Tau:	Schneller, A. N., **243**, 335, 1931.
156	W	Tri:	Hoffmeister, A. N., **202**, 322, 1916.
157	DV	TrA:	Hoffleit, H. B. 884, 1931.
158	Z	UMa:	Gerasimovič, H. B. 856, 1928.
159	RX	UMa:	Enebo, Dombas, **5**, 51.
160	RZ	UMa:	Beyer, Astr. Ab., A. N., **8**, 49, 1930.
161	ST	UMa:	Beyer, Astr. Ab., A. N., **8**, No. 3, 1930.
162	SV	UMa:	Enebo, Dombas, **11**, 35, 1933; Gerasimovič, H. B. 869, 1929; Redman, M. N., **92**, 116, 1931; Beyer, Astr. Ab., A. N., **8**, No. 3, 1930.
163	TZ	UMa:	Beljawsky, N. N. V. S., **5**, 196, 1933.
164	UV	UMa:	Zverev, N. N. V. S., **5**, 107, 1937.
165	V	UMi:	Gerasimovič, H. C. 338, 1929; Redman, M. N., **92**, 117, 1931.
166	RU	Vel:	Payne, H. B. 861, 1928.
167	S	Vul:	Beyer, Astr. Ab., A. N., **8**, 21, 1930; Hufnagel, H. B. 866, 1929.
168	V	Vul:	Gerasimovič, H. C. 321, 1927; Sanford, Ap. J., **79**, 82, 1934.
169	RT	Vul:	Loreta, B. A. F., **2**, 20, 1937.

CHAPTER VI

THE IRREGULAR VARIABLES

> Und ziehe schon an die zehen Jahr
> Herauf, herab und quer und krumm
> Meine Schüler an der Nase herum —
> Und sehe, dass wir nichts wissen können![*]
>
> Goethe

38. Irregular Variables.—After the periodic and semiregular variables have been eliminated there remain a considerable number of variable stars of late spectral class that are still unclassified. All the so-called irregular variables, not otherwise tabulated in this volume, that are known to be of spectral class later than G, are given in Table VI, I. The table may contain a few stars that are not variable at all (like the now discarded "variable" Z Geminorum), and some of the entries may on further examination show regularities (like the eclipsing star VV Cephei, that was placed for twenty years among the irregular variables). The list furnishes the material for many interesting researches, for although many of its members are probably really irregular, some of them are without doubt undetected regular variables.

Such comparatively bright stars of late type, if they were dwarfs, would have considerable proper motions which could not have gone undetected; and so we may conclude that most of the stars of the present list are at least giants. Probably many of the M stars are supergiants, if we are to judge from

[*] And straight or crosswise, wrong or right,
These ten years long with many woes,
I've led my scholars by the nose,—
And see, that nothing can be known!

Bayard Taylor's translation

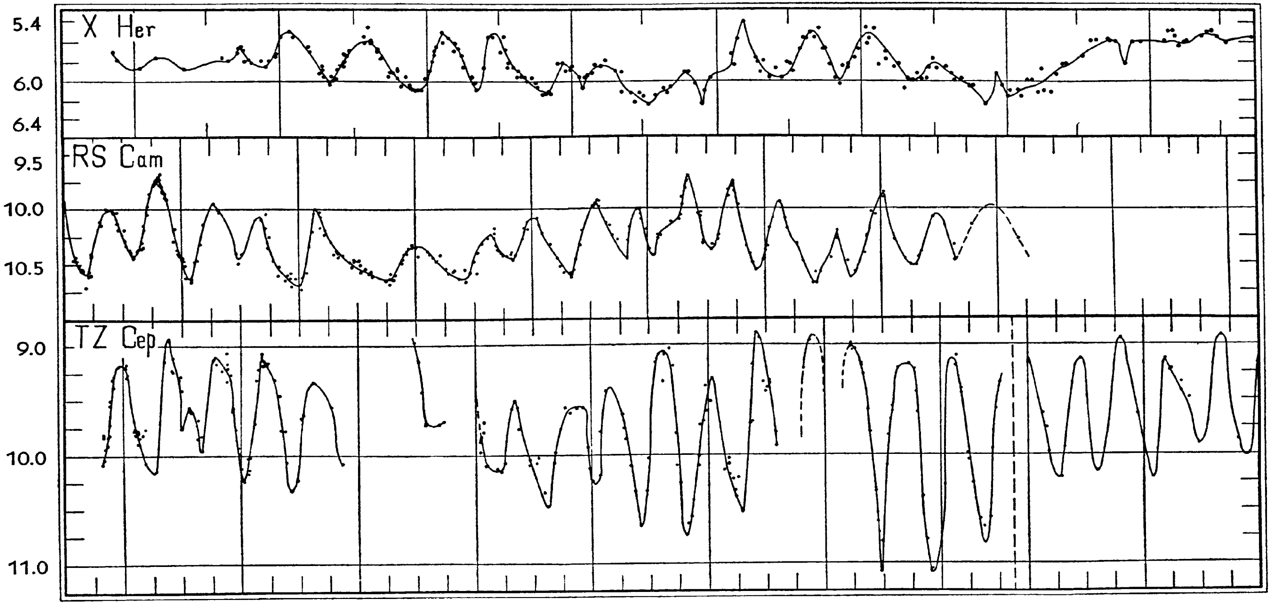

Figure VI, 1.—Typical irregular red variables:

X Herculis	P=100^d	Spectrum Mc	J.D. 2417900—2419550
RS Camelopardalis	166	Mb	2418600—2420650
TZ Cephei	83.1	M0	2422800—2424400 and 2426000—2426200

Sources of observations: X Herculis (visual), Ryves, M.N., 84, 171, 1934.
RS Camelopardalis (photographic), Martin and Plummer, M.N., 76, 612, 1916.
TZ Cephei (visual), Hassenstein, A.N., 250, 265, 1933.

the relations between spectral class, luminosity, and range of variation found for M stars by Stebbins and Huffer.[1]

That some of the stars of Table VI, I are truly irregular in behavior, may be seen from the well observed light curve of X Herculis.[2] It is difficult to draw the line between these and the less regular of the "related stars" of Chapter V. The irregular variations of the group of stars now described are not necessarily incompatible with the more regular changes in the brightness of the members of the Great Sequence; in fact the type of variability displayed by the irregular red variables may affect some abnormal long-period variables, such as SX Scorpii[3], and may even be considered responsible for the unexplained irregularities in the form of the light curve of the ordinary long-period variable.

The few K stars given in the table are probably the most interesting and the simplest of the group for investigation. They should be the subject of *simultaneous* photometric, spectrophotometric, and spectrographic studies, in order to find what relation, if any, exists between their changes of brightness and their (possible) changes of spectrum, color and radial velocity. Such studies will be of great interest in establishing the extent to which the stars are similar to those of the Great Sequence in type of variation. The M and N stars of the table are more difficult, but equally interesting subjects for study, which should be directed along lines similar to those indicated for the K stars. The intensities of the absorption bands (which ought, of course, to be referred to an external source, such as another star of suitable energy distribution) should in these cases furnish a further clue to the nature of the variations. The stars of Table VI, I are recommended for the formation of interesting observing lists of difficult but important objects.

[1] P.N.A.S., 14, 491, 1928.

[2] Ryves, M.N., 84, Plate 7, 1924; Hand. d. Ap., 6, 170, 1928.

[3] ten Bruggencate, Ann. Bosscha Obs., 2, Part 3, C36, 1928.

Table VI, I
Irregular Variables of Known Spectrum

Star	Des.	Max.	Min.	Sp.	Star	Des.	Max.	Min.	Sp.
		m	*m*				*m*	*m*	
RS And	235048	7.0	9.0	Mc	YY Ara	1632*59*	*11.8*	*13.0*	K
SS And	230752	8.9	9.9	M6	V Ari	020911	8.3	9.0	R8
SU And	235943	*10.6*	*11.1*	Nb	RR Ari	015023	5.7	6.4	K0
TZ And	234546	*9.8*	*11.1*	M5	RV Aur	062742	9.2	9.6	Na
UX And	022645	8.2	9.5	M5	SU Aur	044930	9.0	9.8	K?
UY And	023238	*11.0*	[*14.0*	N3	TU Aur	062845	7.7	9.1	Mb
VX And	001444	*10.7*	[*13.8*	Pec.	TW Aur	054945	7.3	9.2	Mc
U Ant	1030*39*	5.7	6.8	Nb	UU Aur	062938	5.1	6.8	M3
R Aps	1446*76*	5.0	6.2	K2	UX Aur	050849	8.0	8.8	M2
V Aps	1455*71*	*10.5*	*11.5*	Mb	UZ Aur	050840	7.7	9.3	Ma
W Aps	1701*74*	*10.8*	*12.2*	M6	AI Aur	062730	*10.1*	*10.8*	M3
θ Aps	1355*76*	5.5	*6.7*	Mbp	Y Boo	141720	7.4	8.2	K0
V Aqr	204102	7.8	10.2	M6e	RV Boo	143532	7.5	8.8	M7e
SZ Aqr	2237*21*	*9.3*	*11.0*	K2	RZ Boo	135829	*10*	*12*	M4
UV Aqr	223801	*12.4*	*15.8*	Mb	S Cae	0453*33*	9.7	10.5	K
BM Aqr	2201*16*	*10*	*11*	Ma	ST Cam	044067	6.9	8.3	Nb
T Aql	184008	8.8	10	Mb	RX Cnc	080825	*8.6*	*11.2*	M8
V Aql	1859*05*	*6.7*	8.2	Np	Y CVn	124045	*7.7*	*8.8*	N3
TW Aql	194613	*10.6*	*12.7*	K?	W CMi	074305	*10.3*	*11.3*	R8
TZ Aql	2025*05*	8.5	9.5	M6	RS Cap	2101*16*	8.6	9.3	Mc
UV Aql	185414	7.9	9.0	N4	UU Cap	213014	*9.2*	*10.9*	Mb
UW Aql	185200	8.7	9.3	M0	RR Car	0954*58*	*8.1*	*9.6*	M6
LU Aql	193415	*10.9*	*12.0*	M1	RU Car	0913*65*	*10.9*	*12.1*	Mb
T Ara	1654*54*	*9.9*	*11.0*	Nb	RU Car	0913*65*	*10.9*	*12.1*	Nb
W Ara	1749*49*	*10.0*	*10.7*	Mc	BZ Car	1050*61*	9.0	*9.7*	K5

TABLE VI, I—*Continued*

Star	Des.	Max.	Min.	Sp.	Star	Des.	Max.	Min.	Sp.
		m	*m*				*m*	*m*	
DI Car	1111*69*	*11.8*	*13.2*	Pec.	CO Cyg	205744	*9.4*	*10.6*	K6
ST Cas	001249	8.1	8.6	Nb	CY Cyg	204345	*9.9*	*11.7*	S
WW Cas	012757	9.1	11.7	N3	GY Cyg	215848	*11.1*	*13.1*	Mcp
WZ Cas	235659	6.9	8.5	Nlp	PU Cyg	195237	*13.7*	*14.5*	N
XZ Cas	011660	*10.3*	)*11.8*	M0	QZ Cyg	195537	*11.2*	*12.4*	M3
α Cas	003455	2.1	2.6	G8	V335 Cyg	195637	*13.8*	*14.4*	M1
Y Cen	1425*59*	*7.7*	*8.8*	Mc	U Del	204017	5.6	7.5	Mb
RW Cen	1102*54*	*10.2*	*11.2*	Nb	RS Del	202415	*8.9*	*9.8*	Mc
AD Cen	1148*58*	*9.0*	*12.*	M1e	RY Dra	125266	6.1	7.1	N4p
AW Cen	1307*56*	*10.0*	*10.7*	Mb	TY Dra	173557	8.8	9.9	Mc
RW Cep	221955	6.8	7.5	Ma	UW Dra	175554	7.0	8.0	K5p
SW Cep	212362	8.0	9.0	Mc	UX Dra	192576	5.8	7.2	N0
X CrA	1802*45*	*9.9*	*11.6*	Mc	VW Dra	171516	6.3	7.0	K0
RU CrB	153126	8.8	11.4	Mc	T Eql	211008	9.6	10.8	M3
S Crv	1232*16*	*9.6*	*10.5*	M8	V Eri	0359*16*	8.3	9.4	Mc
R Cra	1055*17*	*9.8*	*10.4*	Mc	RR Eri	0247*08*	7.2	8.5	Mb
RR Cyg	204244	*12.9*	*13.8*	M?	UW Eri	0259*14*	*9.5*	*10.*	Mb
RS Cyg	200938	6.8	10.3	N0pe	VX Eri	0320*12*	*9*	*10*	Mb
RV Cyg	213937	7.1	9.3	N5	VY Eri	0336*11*	*9*	*10*	Mb
RY Cyg	200635	9.2	11.0	Nb	Y Gem	073520	8.5	10.0	M6e
SV Cyg	194232	8.5	9.4	N3	TU Gem	060426	7.4	8.3	N3
AC Cyg	200949	*9.2*	*10.0*	Mc	VW Gem	063531	8.5	9	Na
AD Cyg	202732	8.3	9.9	S	X Her	155947	5.8	7.2	Mc(e)
AW Cyg	192545	8.0	10.2	N3	ST Her	154748	6.8	8.5	Mc
AZ Cyg	205446	8.1	9.4	Map	UW Her	171036	7.5	8.5	M4e

TABLE VI, I—*Continued*

Star	Des.	Max.	Min.	Sp.	Star	Des.	Max.	Min.	Sp.
		m	*m*				*m*	*m*	
AN Her	173120	*9.1*	*10.4*	M4	V Nor	1602*48*	*8.9*	*9.9*	Mb
BE Her	162129	8.4	9.4	M3	ϰ Oph	165209	*4.1*	*5.0*	K0
α Her	171014	3.1	3.9	M5	RT Ori	052707	7.5	8.9	Nb
g Her	162542	4.4	5.6	Mbp	CI Ori	0524*01*	*5.1*	*6.8*	K5
U Hya	1032*12*	4.8	5.9	N2	CK Ori	052504	*6.7*	*7.3*	K0
Y Hya	094622	6.5	8.0	Np	DP Ori	055610	*10.3*	*12.9*	M0
RV Hya	0834*09*	*7.6*	8.3	Mb	EV Ori	051009	*11.7*	*12.9*	K0
RV Lac	224049	9.5	11.4	k	X Pav	2003*60*	*9.0*	*10.2*	Mc
SX Lac	225134	*9.4*	*10.2*	K2	SX Pav	2119*69*	5.3	6.3	Mb
TV Lac	225153	*11.7*	*12.7*	Nb	SV Peg	220134	8.4	9.0	Mc
T Lup	1415*49*	8.3	8.9	Nb	TT Peg	000126	9.0	10.3	M3
V Lup	1452*53*	*9.7*	*10.7*	Nb	AD Peg	221926	11.1	13.0	g5
RS Lup	1416*47*	*10.7*	*11.7*	Nb	BD Peg	223827	*8.5*	*9.5*	M8
RU Lup	1550*37*	*9.0*	*11.0*	Pec.	S Per	021558	7.2	12.2	M5
Y Lyn	072046	6.9	7.4	Mb	T Per	021258	8.0	9.0	K5
R Lyr	185243	4.0	4.5	M5	RS Per	021556	8.0	9.4	M6
T Lyr	182836	7.8	9.6	N3	TV Per	023735	*9*	*11*	K0
SY Lyr	183728	*10.9*	*11.7*	Mc	XX Per	015654	9.6	10.4	Ma
XY Lyr	183439	5.8	6.8	Mb	YZ Per	023156	*7.6*	8.3	M2
EY Lyr	183731	9.5	10.5	Mb	AC Per	033834	*10.2*	*12.4*	M3
W Mon	064*707*	9.7	[12.2	N?	AE Per	025343	*9.4*	*10.2*	M3
Z Mon	0628*08*	9.0	*10.1*	K5	ϱ Per	025838	3.2	4.1	Mb
RV Mon	065306	7.0	8.2	Nb	Z Psc	011025	6.9	8.1	N0
SU Mon	073*710*	8.0	10.7	S	ST Psc	010826	*10.9*	*12.7*	M5
SX Mon	064604	8.7	9.4	Mb	SV Psc	014118	*9.7*	*11.0*	M5

TABLE VI, I—*Continued*

Star	Des.	Max.	Min.	Sp.	Star	Des.	Max.	Min.	Sp.
		m	*m*				*m*	*m*	
RT Pup	0801*38*	*9.4*	*11.6*	Nb	RX Sct	1831*07*	*9.7*	*12.0*	N3
RU Pup	0803*22*	*9.4*	*11.6*	Nb	R Sex	0937*07*	*9.7*	*10.6*	Mb
RY Pup	0727*34*	7.0	8.0	K5	V Tel	1910*50*	*9.2*	*10.6*	Mc
T Sge	191717	8.3	9.5	M4	X TrA	150469	*8.2*	*10.0*	Nb
SS Sgr	1824*16*	8.0	10.5	N3	U UMa	100860	6.1	6.8	Map
UX Sgr	1849*16*	7.6	8.3	Nb	Y UMa	123556	7.7	9.3	Mcp
AO Sgr	1805*29*	*9.5*	*10.7*	Ma	TV UMa	114036	*8.2*	*9.0*	Mb
AQ Sgr	1928*16*	6.6	7.6	N3	U Vel	0929*45*	8.1	8.5	Mb
SS Sco	1648*32*	7.5	9.5	K2	X Vel	0951*41*	*9.5*	*11.8*	Nb
ST Sco	1630*31*	7.8	9.7	R5	RT Vir	125705	8.0	9.0	M7
SU Sco	1634*32*	7.5	9.0	N0	RW Vir	1202*06*	7.0	8.2	Mb
BM Sco	1734*32*	*7.0*	*9.2*	K0	RX Vir	1159*05*	8.0	8.4	K0
Y Scl	2303*30*	*7.8*	*8.9*	Mb	RY Vir	133618	*8.3*	*9.3*	Nb
S Sct	1844*08*	7.0	8.0	N3	SW Vir	1308*02*	6.8	8.1	Mc
T Sct	1850*08*	8.8	9.3	N3	TZ Vir	115903	8.6	10.5	Ma
RT Sct	1844*10*	9.1	9.7	M1	BD Vul	203326	*12.*	*15.*	N

D

THE CATACLYSMIC VARIABLES

CHAPTER VII

THE CATACLYSMIC VARIABLES, I

THE NOVAE

Dixitque Deus: Fiat lux. Et facta est lux.

The stars that have hitherto been described vary with a certain regularity and restraint, and show definite periodicities, although some of them are erratic at times or in cycles. But the subdivision now to be discussed, the Cataclysmic Variables, contains stars that vary in a more truly irregular manner, not only in periodicity, but also in form of light curve and spectroscopic behavior. Among them we include the novae and SS Cygni stars, and the R Coronae Borealis stars.

For rough purposes of analysis the cataclysmic variables may be divided into three groups: stars that become suddenly faint, regaining their former brightness slowly; stars that become suddenly bright, regaining their former magnitude slowly; and stars that become bright and faint in an apparently erratic manner. There are not any known stars that habitually become slowly faint, or slowly bright, and then return suddenly to their former brightness.

The types of variables that fall respectively in the three classes are as follows:

I. Stars that become suddenly faint	
a. R. Coronae Borealis stars	
b. Quasi-R Coronae Borealis stars	Chapter X
II. Stars that become suddenly bright	
a. Novae	
i. Supernovae	Chapter VIII
ii. Novae	Chapter VII
iii. Subnovae	Chapter VII
b. SS Cygni stars (dwarf novae)	Chapter IX

III. Stars that become erratically bright and faint
  - a. Nebular variables — Chapter XI
  - b. Variables with nebular spectra
  - c. "Irregular" variables
  - d. Stars with variable atmospheres

The stars in the first class are all yellow or red giants; the second class contains chiefly dwarf stars (at normal brightness); the members of the third class are distributed between dwarfs and giants, according to the type of variability.

39. **Novae:** *i. Definitions.*—Novae are recognized by a sudden brightening of several magnitudes, usually followed by a brief period of maximum brightness and a decline slower than the rise. For all the more typical novae that have been spectroscopically observed, these phenomena have been found to be accompanied by an expansion of the surface of the star, first conspicuously indicated by the velocities of the absorption lines, then by the development of the corresponding widened bright lines, and lastly by the appearance of a spectrum showing nebular characteristics. Spectral behavior according to some such pattern has therefore become an additional criterion for membership in the nova class. However, as the spectra of certain stars may show nebular characteristics, even though they are definite members of other groups of variables (for example, R Aquarii, a long period variable) or may even be apparently of constant brightness (for example, H.D. 45677), the occurrence of any one of these spectral phenomena does not necessarily indicate that the star should be regarded as a nova. In fact the suffix q, indicating the P Cygni type of bright lines, is intended to permit the description of spectroscopic features resembling those of novae (Class Q) for stars not necessarily members of that group.[1] A star that has shown a sudden brightening of large range, but which does not show, in some form, the spectral phenomena just described, cannot be considered a nova, and may possibly, for instance, be a long period variable of very long period or peculiar behavior (Nova Aquilae 1919 was such a star). A star that showed all the spectral features mentioned,

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[1] See Table VIII, I, where P Cygni and η Carinae are included among the novae.

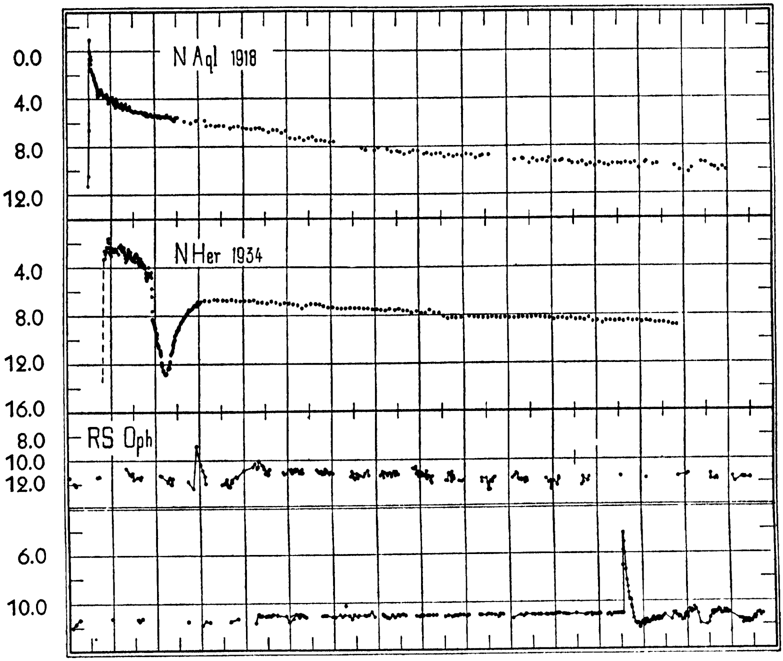

Figure VII, 1.—Light curves of three novae of different types:

Nova Aquilae 1918	from J.D.	2421700 to 2423300
Nova Herculis 1934		2427700 to 2429200
Nova RS Ophiuchi		2413000 to 2429000

All the light curves have been compiled from the visual observations of the A.A.V.S.O. and other groups of observers by Mr. Campbell, with whose kind permission they are reproduced here.

but which changed only slightly or slowly in brightness, may be considered as a nova of unusual type (RT Serpentis, perhaps, furnishes an example). A star that showed a spectrum resembling those reached by many novae at or about their return to their original brightness might possibly be tentatively regarded as an ex-nova (such a case is furnished by V Sagittae); but as a slight stretching of this definition would include all the planetary nebulae (which may be possible ex-novae, but which certainly cannot be definitely stated to be so),[2] it must be used with caution, and perhaps confined to stars that are now variable in brightness.

Despite the indefinite nature of the criteria just summarized, and the wide variety of the objects that are included in the class so formed, all such stars may well be treated together, for they have much in common. A list of all the stars that have been ascribed to the class of novae during the last century,[3] and a few well-observed objects that appeared earlier, is contained in Table VII, I. Comparatively few of the objects so classed have been rejected as probably not novae. The list is restricted to galactic novae, only a few extragalactic objects, such as S Andromedae, which have received constellation designations, being excluded. Table VII, II contains a summary of the novae of normal type that have been observed in stellar systems other than the galaxy. The reference is either to the Geschichte und Literatur, or to the paper in which the nature of the star was established. The very luminous supernovae, which form a class distinct in some ways from the normal novae, are tabulated and discussed in a later chapter.

40. General Properties of Novae: *i. Distribution.*—The galactic coordinates given in Table VII, I, indicate that the majority of novae are in very low galactic latitude, and also that their distribution in galactic longitude is far from uniform.

Gal. Long.	Mean Gal. Lat.	No. of Stars	Gal. Long.	Mean Gal. Lat.	No. of Stars
°	°		°	°	
0–44	11.5	18	180–224	4.0	2
45–89	6.0	4	225–269	7.0	6
90–134	15.0	5	270–314	5.0	7
135–179	11.0	8	315–359	8.0	33

The mean galactic latitude for all eighty-three novae is 9.3. Four stars of high galactic latitude have been excluded: Nova Bootis 1860 (+67°); Nova Comae 1877 (+70°); Nova Leonis 1918 (+60°); and Nova Virginis 1871 (+69°); none of them was well-observed, and the last is probably not a nova.

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[2] See page 254.

[3] Stratton, Handbuch d.Ap., 6, 254, 1928; ibid., 7, 671, 1936.

TABLE VII, II

NORMAL NOVAE IN EXTRAGALACTIC SYSTEMS

System	No. of Novae	Type of System	Reference
NGC 224=M31	115	Spiral (Andromeda) nebula	1
598= 33	6	Spiral nebula	2
3031= 81	1	Spiral nebula	3
5457—8= 101	3	Spiral nebula	4
6093= 80	1	Globular cluster	5
6822 ..	0	Magellanic type system	6
Large Magellanic Cloud	1		7
Small Magellanic Cloud	1		8

1. "Normal novae flare up at the rate of 25 or 30 per year . . . The light curves, luminosities, and spectra (Humason, P.A.S.P., 44, 381, 1932) are similar to those of galactic novae. The absolute magnitudes at maximum are symmetrically distributed around the mean value, $M=-5.5$, with a dispersion of about 0.5 mag. The brightest observed maximum is $M=-6.7$ . . ." (Hubble, The Realm of the Nebulae, 134, 1936).
2. Hubble (The Realm of the Nebulae, 134, 1936) states that all six are apparently normal.
3. Ritchey, P.A.S.P., 29, 210, 1917; the star is, however, probably a Cepheid.
4. Hubble and Humason, Mt.W.Contr. 427, 1931; see Table VIII, note 17.
5. T Scorpii: "If it is an actual member of the cluster, its absolute magnitude at maximum . . . was —9.2, three magnitudes brighter than the average galactic nova" (Shapley, Star Clusters, 55, 1930); we assume it a foreground object of normal luminosity.
6. Hubble, The Realm of the Nebulae, 1936.
7. RY Doradus; Luyten, H.B. 847, 851, 1927; see Shapley, H.B. 898, 1935.
8. Shapley and Hughes, H.B. 898, 1935.

It cannot be stated at present that novae occur preferentially in nebulous regions; Nova Persei 1901 and η Carinae are the only ones that undoubtedly appeared in or near diffuse nebulosity. The development of nebulous discs at some time after the outburst is a different matter, the nebulosity in this case being the product of the nova itself. In the past, when such objects as T Tauri[4] were considered to be novae, their obvious association with nebulae strengthened the idea that novae tended to appear in nebulous regions. The nebulae surrounding Nova Persei and η Carinae are discussed under the heading of the special properties of those stars.

ii. Frequency of Novae.—The conclusions of Bailey[5] still summarize our knowledge of the frequency of galactic novae; he

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[4] See page 306.

[5] P.A.S.P., 24, 554, 1921.

Table VII, I

Galactic Novae

Nova*		Position	λ	β	Max.	Min.	Spec.†	Reference	Remarks
					m	m			
(And 1901)	Z	232848	78°	—12°	8.3—	12.8	O+M	See p. 315.	Not a nova.
Aqr 1907.6	VY	210*609*	10	—37	8.4—	[16		H.B. 826.	
Aql 1899	No. 1	191*400*	4	— 8	6.8—	[15.4	Q	G.u.L., I, 2, 442.	
Aql 1905.6	No. 2	185*604*	359	— 6	6.5—	[17	Q	G.u.L., I, 2, 442.	
Aql 1918	No. 3	184300	1	— 1	—1.4—	10.8	Q	G.u.L., II, 1, 80.	
(Aql 1919)	No. 4	191201	5	— 6	10.4—	15.0	RO	G.u.L., II, 1, 85.	Not a nova[1].
Aql 1925.7	DO	192*506*	0	—13	8.5—	[16.5	Q	H.B. 826.	
Aql 1927	EL	185*003*	359	— 4	8.0—	[16	Q	H.B. 851.	
Aql 1936.6	V356	191201	8	— 6	7.6—	[16	Q	H.A.C., 388; Pop. Astr., **45**, 219.	
Aql 1936.7	V368	192107	11	— 6	6 —	[13	Q	H.A.C. 396.	
Ara 1862		173*145*	313	— 9	5 —	[11		Tebbutt, M.N., 38, 330.	Probably a nova.
Ara 1910.3		163*252*	301	— 5	6.0—	17.5	Q	G.u.L., I, 2, 437.	
Ari 1854	No. 1	024217	128	—36	9.5—	[14.5		G.u.L., I, 2, 420.	
(Ari 1855)	W	031428	127	—22	9.5—	[14		G.u.L., I, 1, 89; II, 1, 93.	Doubtful; may be a long period variable.
?Ari 1905	No. 2	031819	134	—28	12 —	[15		Wolf, A.N., 4056.	Probably a nova.
Aur 1891	T	052530	145	0	4.2—	15.0	Q	G.u.L., I, 2, 426.	
Boo 1860	T	140819	342	+67	9.7—	[14		G.u.L., I, 1, 379 (No. 799).	
Car 1843	η	104*259*	255	0	—1 —	8	Feq.	G.u.L., I, 1, 304 (No. 614).	Spectrum 70 yrs. post-max.
Car 1895	RS	110*261*	259	— 1	7.4—	[15.8	Q	G.u.L., I, 2, 433.	
[Cas 1572]	B	001863	88	+ 2	—3.5—	13.7	M3:	See Table VIII, II.	Spectrum is probably of nearby star.

TABLE VII, I—*Continued*

Nova*		Position	λ	β	Max.	Min.	Spec.†	Reference	Remarks
					m	m			
Cen 1931	MT	113760	263	+ 1	8.6—	[14		Uitterdijk, B.A.N., 7, 176, 1934.	
Cir 1906.1		144059	285	− 1	9.5—	15.0		G.u.L., I, 2, 434.	
Cir 1914	AI	143868	279	−10	10.9—	[16.5		H.B. 883, 1931.	
Cir 1926	X	143264	282	− 5	6.5—	[16.7	Q	Becker, A. N. 5668; Miss Cannon, H.B. 872.	
?Com 1877		140121	345	+70	4.5—	[10		Schwab, A.N., 155, 220.	Probably a nova.
CrB 1866	T	155426	10	+46	2.0—	10.6	Q	G.u.L., I, 2, 435.	
Cyg 1600	P=No. 1	201337	44	+ 0	3 —	[6	Beq	G.u.L., I, 2, 444.	Spectrum is 300 years post-max.
Cyg 1876	Q=No. 2	213642	58	− 8	3.0—	15.4	Q	G.u.L., I, 2, 446.	
(Cyg 1909)	AG	194836	40	+ 4	11 —	17		A.N., 186, 125; M.N., 73, 500.	Now known to be long per. var.
Cyg 1920	No. 3	195453	55	+12	1.5—	[16	Q	G.u.L., II, 2, 62.	
(Gem 1856)	SY	063331	152	+13	9.4—	[14		G.u.L., II, 2, 108.	Probably not a nova.
?Gem 1856	VZ	080031	160	+30	8.7—	[16.2		G.u.L., II, 2, 112.	Probably a nova.
?Gem 1892		065217	144	+11				Hand.d.Ap., 6, 254.	Probably not a nova.
Gem 1903	No. 1	063730	153	+13	7.3—	16.8	Q	G.u.L., I, 2, 429.	
Gem 1912	No. 2	064832	151	+16	3.7—	14.5	Q	G.u.L., I, 2, 430.	
(Gem 1933)	AW	071628	158	+21	13.2—	[17.0		U.A.I. Circ. 430, 431, 432, 434; Kukarkin, N.N.V.S., 4, 171, 1933.	Probably an SS Cyg star.
Her 1934	DQ	180445	39	+25	1.3—	15	Q		
Lac 1910		223052	71	− 4	5.0—	14.4	Q	G.u.L., I, 2, 448.	
Lac 1936	CP	221255	70	− 1	2.2—	15	Q	H.A.C. 380.	
(Leo 1855)	U	101814	196	+54	9.5—	[13		H.B. 896.	Probably not a nova.

TABLE VII, I—*Continued*

Nova*		Position	λ	β	Max.	Min.	Spec.†	Reference	Remarks
					m	*m*			
?Leo 1918	RZ	113202	236	+60	11.5—	[16		Wolf, A.N., 4998; Beljawsky, A.N. 5261.	Perhaps a nova; observed only 2 nights.
?Lyr 1905	SU	184836	34	+15	11.6—	[17		G.u.L., I (No. 1228).	Probably a nova.
Lyr 1919		184829	28	+11	6.5—	14.9	Q	G.u.L., II, 2, 246.	
Mon 1918		072106	191	+ 3	5.4—	15.1	Q	G.u.L. II, 2, 265.	
Nor 1893.5	(R)= No. 1	152250	295	+ 4	6.9—	[16.3	Q	G.u.L., I, 2, 435.	Designation R early discontinued and given to another star.
Nor 1920	No. 2	153152	295	+ 2	9 —	16.5		Bailey, H.B. 734.	
Oph 1604		172421	333	— 4	—2.5—	14		See Table VIII, II.	Supernova.
Oph 1848	No. 2‡	165312	336	+15	5.0—	13.0		G.u.L., I, 2, 438.	
Oph 1897	BB	171724	328	+ 4	11.3—	[18		H.B. 835.	
Oph 1901	RS=No.3	174406	348	+ 8	4.3—	11.8	Q	G.u.L., II, 2, 288.	Recurred in 1933.
Oph 1919	No. 4	180811	7	+12	7.5—	[15	Q	G.u.L., II, 2, 353.	
?Ori 1677		055220?	157	— 1	6.0—	[12		Hand.d.Ap., 6, 252.	See note^2.
Ori 1916.1		051501	169	—17	11.5—	[15		Thiele, A.N., 202, 213.	
Per 1887	V=No.1	015456	101	— 4	9.0—	[16.1	Q	H.C. 4, 1895.	Chandler's W Per.
Per 1901	No. 2	032443	119	— 9	0.0—	14.0	Q	G.u.L., I, 2, 421.	
?Per 1912	UW	020556	102	— 3	13.5—	[16.5		G.u.L., I, 2, 52 (No. 90).	Probably a nova.
Pic 1925	RR	063262	239	—25	1.0—	12.7	Qp	Spencer Jones, Ann. Cape Obs., 9.	
(Psc 1907)		......	..	..	...	...		Reinmuth and Schlier, A.N., 253, 423.	Not a star.
Pup 1902.8		080826	214	+ 5	7 —	[16		H.B. 760.	
Pyx 1890	T	090032	225	+10	6.5—	14.1	Q	Hand.d.Ap., 6, 66.	Recurred in 1902 and 1920.

TABLE VII, I—*Continued*

Nova*			Position	λ	β	Max.	Min.	Spec.†	Reference	Remarks
						m	*m*			
Sge	1783	No. 1	192717	21	−2	6	[15		G.u.L., I, **2**, 443.	
Sge	1913	No. 2	200217	26	−9	7.2	[15		H.C. 219.	A "sub-nova."
?..	Sge	V	201520	30	−9	9.5	13.2	Ob	H.B. 894; M.N., **92**, 715.	An ex-nova?
Sgr	1897	LQ	182227	333	−9	13.0	[16.5		H.B. 859.	
Sgr	1898.2	No. 1	1855*13*	350	−10	4.7	[16	Q	G.u.L., I, **2**, 441.	
Sgr	1899.6	No. 3	1813*25*	335	−7	8.5	15.0		G.u.L., **2**, 441.	
Sgr	1900.7	HS	1822*21*	349	−5	11.5	16.5		H.B. 851.	
Sgr	1901.4	No. 4	1800*27*	331	−5	10.3	[16.1		H.C. 164.	
Sgr	1905	No. 6	1802*32*	327	−8	7.1	[12		H.B. 714.	
Sgr	1910.4	No. 2	1753*27*	331	−4	7.8	16.3	Q	G.u.L., I, **2**, 440.	
?Sgr	1912		1828*29*	332	−11	11	[17		U.C. 37, 302.	Not a typical nova.
?Sgr	1914		1828*26*	335	−10	14.2	[17		U.C. 37, 362.	Not a typical nova.
Sgr	1914.6		1834*28*	331	−12	15.5	[17		U.C. 20, 152; 37, 302.	Seen only on three plates of July, 1914.
Sgr	1914.6	No. 7	1800*31*	328	−7	8	[17		H.B. 733.	
Sgr	1917.5	BS	1820*27*	334	−9	9.2	[16	Q	H.B. 782.	
Sgr	1919	No. 5	1825*29*	333	−11	7	14		H.B. 693.	
Sgr	1924.4	GR	1816*25*	335	−7	11.4	16.6		H.B. 851.	
Sgr	1924.5	FL	1753*34*	324	−7	8.3	[15		H.B. 847.	
Sgr	1926	FM	1810*23*	333	−5	10.6	[16.5		H.B. 843.	
Sgr	1926.7	KY	1755*26*	331	−3	10.6	[16.5		H.B. 861.	
Sgr	1927	V363	1905*30*	335	−19	8.8	[16	Q	H.B. 878.	
Sgr	1930	V441	1815*25*	334	−7	8.7	16.0	Q	H.B. 890.	
Sgr	1936.32		1749*27*	330	−2	6.5	[12.5	Q	H.B. 907.	
Sgr	1936.37		1813*26*	334	−7	10.8	[16.5	Q	H.B. 907.	
Sgr	1936.7		1802*34*	326	−9	4.5	[15	Q	H.A.C. 392, 393; H.B. 907.	

TABLE VII, I—*Continued*

Nova*			Position	λ	β	Max.	Min.	Spec.†	Reference	Remarks
						m	*m*			
Sgr	..	FN	1848*19*	344	− 9	8.5—	13.5		H.B. 861; A.N., 230, 155.	
Sco	1863	U	1616*17*	326	+20	9.1—	[15		G.u.L., I, 2, 49.	Discovered by Pogson. Müller and Hartwig consider this star a nova.
Sco	1893	V384	1754*35*	324	− 7	12.3—	[15		H.B. 902.	
Sco	1901	V382	1745*35*	323	− 6	9.4—	[16.5		H.B. 902.	
?Sco	1906.5	No. 2‡	1747*34*	324	− 6	8.8—	[15.5		H.C. 137.	Not a typical nova.
Sco	1917		1647*29*	321	+ 7	6.5—	[17		G.u.L., II, 2, 354.	Also called Nova Oph 1917, or Nova Oph No. 5.
Sco	1922	No. 3	1741*36*	321	− 6	9.9—	[15		H.B. 773.	
Sco	1928	KP	1737*35*	322	− 5	9.4—	[16.5		H.B. 870.	
Ser	1909	RT	1734*11*	343	+ 8	10.6—	[16		See page 264.	
Ser	1903	X	1613*02*	338	+30	8.9—	[15.4		H.A., 84, 198.	
Tau	1929	XX	051316	155	−10	6.0—	[16	Q	A.N., 234, 409; ibid., 235, 435.	
Vel	1905.9		1057*53*	255	+ 5	9.7—	[16.5	Q	H.C. 121.	
(Vir	1871)	X	115609	240	+69	8 —	11.6		Pop.Astr., 44, 83.	Probably not a nova.
Vul	1670		194227	31	− 0	2.7—	[16.5		G.u.L., I, 2, 443.	
?Vul	1923	SW	195422	29	− 5	15 —	[17.5		A.N., 220, 256.	Possibly a nova.

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* The first designation given is in the system that seems most satisfactory at present—that according to time of maximum, or to time of the observation presumably nearest to maximum in time. The designations that follow are letters and numbers by which the nova has also been known. Objects that are considered not to be novae are enclosed in parentheses. Objects that are somewhat doubtful novae are preceded by a note of interrogation. Supernovae are enclosed in brackets.

† We have adopted the notation recommended by the Commission on Spectral Classification of the International Astronomical Union, Rome meeting, 1922.

‡ The numbering of novae in Ophiuchus and Scorpio is confused, as a result of overlapping boundaries adopted for these two constellations: we have given the numbering as tabulated by Prager in his "Katalog und Ephemeriden."

[1] The authors consider that Graff's conclusion (B.Z., 5, Nos. 41, 49) is correct, and that the star is a long period variable, possibly similar to W Orionis; they had reached the same conclusion independently.

[2] The star recurred in about 1750, and a third apparition was apparently witnessed by Shackleton in 1892 (B.A.A. Journ., 4, 215, 1894). There is here the bare suggestion of a period of between seventy and eighty years. The star should be looked for again. In any case it is a peculiar object.

estimated that 25 galactic novae of the ninth magnitude or brighter, and one or two of the sixth magnitude or brighter, may be expected to occur each year. The frequency of novae in the Andromeda nebula seems to be of the same order.[6]

There is much interest in the possibility that all novae may be recurrent, the known recurrent novae (Nova Ophiuchi 1901, Nova Pyxidis 1890, and possibly Nova Orionis 1677) being linked up with the very similar SS Cygni stars of shorter cycle, and the suggestion is made that the cycles of the majority of novae are much longer. A few estimates of mean cycle for the normal novae, which deserve mention rather than discussion, lead to results of the order of 10^8 or 10^6 years.[7]

iii. Luminosities of Novae.—Various studies of galactic and extragalactic novae lead to the conclusion that the dispersion in absolute magnitude at maximum is fairly small. The average of a number of individual determinations of absolute visual magnitude given by Stratton[8] is -6.6. From extensive studies of the magnitudes of galactic and extragalactic novae, Lundmark[9] arrives at values between -5.5 and -7.0. For the novae in the Andromeda Nebula, Hubble[10] has obtained a mean absolute photographic magnitude of -5.7, and his result for Messier 33 is very similar, as are the absolute magnitudes derived from Harvard measures of the brightness of the two isolated novae in the Magellanic Clouds (one of which has, however, a somewhat abnormal light curve).

For the parallaxes of individual galactic novae a number of special methods are available. Direct measures of parallax and proper motion exist for the objects listed in Table VII, III. Provisional proper motions for six other novae were given by Lampland[11]; all are small, and confirm the more accurate values of Table VII, III.

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[6] Stratton, Handbuch d.Ap., 6, 260, 1928.

[7] Lönnquist, Lund Circ. 7, 1932; von Zeipel and Lundmark, quoted by Lönnquist, *op.cit.*

[8] Handb.d.Ap., 7, 674, 1936.

[9] Ups.Medd., No. 30, 1927; Lund Medd. Series I, No. 135, 1933; Lund Circ. 10, 1934; see also Luplau-Janssen and Haarch, A.N., 211, 88, 1920.

[10] Mt.W.Contr. 376, 1929.

[11] Pop.Astr., 29, 221, 1921.

TABLE VII, III

PARALLAXES AND PROPER MOTIONS FOR GALACTIC NOVAE

Nova	Parallax		Proper Motion	Ref.
	"	"	"	
N Aql 1918	—0.002±	0.004	0.02	1
N Cyg 1600	0.006	0.010	0.014	1
N Cyg 1920	0.010	0.005	....	1
N Gem 1912	0.001	0.008	0.02	1
N Lac 1910	0.002	0.007	....	1
N Lyr 1919	0.015	0.007	....	2
N Oph 1919	0.005	0.008	....	3
N Per 1901	0.011	0.003	0.02	1
N Pic 1925	—0.003	0.007	0.05	1
N Sge 1913	0.020	0.005	0.079	4

1. Schlesinger, General Catalogue of Stellar Parallaxes, Yale Univ., 1935.
2. Van Maanen, A.J., 41, 122, 1931.
3. Mount Wilson Rept., p. 95, 1924.
4. Van Maanen, P.A.S.P., 46, 229, 1934.

Expanding nebular discs surrounding bright novae may be used, in conjunction with an estimate of the linear velocity of the expanding material (usually assumed equal to the observed radial velocity, perhaps resolved, as in the case of Nova Herculis, in the direction of the observed transverse motion) to determine the distance of the nova. Such estimates are given for the novae listed in Table VII, IV.

TABLE VII, IV

PARALLAXES FROM EXPANDING NEBULAR DISCS

Nova	Observed Rate of Expansion	Adopted Radial Velocity	Deduced Parallax	Deduced Absolute Magnitude	Reference
	sec/ann.	km/sec	"	m	
N Aql 1918	1.0	1700	0.0028	—9.15	1
N Her 1934	0.27	300	0.002	—6.9	2
N Per 1901	0.4	1200	0.00158	—9.0	3
Nucleus of Crab Nebula	0.134 to 0.178	1300	0.0007	....	4

1. Hubble and Duncan, Mt.W.Contr. 355, 1927.
2. Kuiper, P.A.S.P., 47, 228, 267, 1935; Ap.J., 86, 102, 1937; van Biesbroeck, Ap.J., 82, 434, 1935.
3. Hubble and Duncan, P.A.S.P., 46, 229, 1934; Humason, P.A.S.P., 46, 229, 1935.
4. Duncan, P.N.A.S., 7, 179, 1921; Mayall, P.A.S.P., 49, 101, 1937.

The determination of parallaxes and absolute magnitudes from the apparent velocity of expansion of nebular discs is, however, subject to large uncertainties. There is scarcely a nova of which it can be stated that the ejected nebulosity has spherical symmetry, or that its velocity in all directions is equal and constant. Even the hypothesis of spheroidal symmetry does not meet any known case.* The stars must be considered separately, and none of them is as yet sufficiently well observed to permit definite conclusions.

The fore-and-aft symmetry displayed by Nova Aquilae 1918 suggests that the ejection was directed almost in the line of sight, or at least was less intense in the transverse direction.[12] Therefore the directly observed transverse velocity cannot be identified with the spectroscopically observed radial velocity, but with the component of that velocity, resolved perpendicular to the line of sight, that was present for the actual matter observed. The relation of Hubble and Duncan, instead of being given by:

$$D = 0.211\, r,$$

where D is the distance and r the observed radial velocity, for an expansion of $1''.0$ per year, will be given by:

$$D \sin \theta = 0.211\, r \cos \theta,$$

where the material is ejected in a line making an angle θ with the line of sight. For Nova Aquilae, this angle is almost zero, and the observed expansion of material is the result of the fact that the ejection was not along a line, but filled a finite solid angle. For example, if the expanding material effectively filled a solid angle of 20°, the spectroscopic observations would be satisfied, and the absolute magnitude would be about —7, rather than —9.

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* Real differences in the velocities of material traveling toward and from the observer have been noted for Nova Persei nebulosity and for the Crab Nebula (the only two novae for which the structure has hitherto been sufficiently well defined for this measure to be made). For Nova Persei and Nova Herculis the ejected nebulosity is visibly non-spherical in form, and Nova Pictoris (*q.v.*) provides another instance. Nova Aquilae is known from spectroscopic evidence to have presented a fore-and-aft symmetry. The Crab Nebula is obviously elliptical in projection, probably roughly spheroidal in shape. For Nova Persei a change in the velocity of the nebulosity has been suspected, though possibly it is not real.

[12] *See* Menzel and Payne, P.NA.S., 19, 641, 1933.

Nova Herculis 1934 appears to be an instance of ejection of matter with an angle of about 45° to the line of sight.[13] Here the old and new formulae give the same result, near to —7 absolute magnitude.

For Nova Persei the spectroscopic evidence as to the angle of ejection is less clear than for the two other stars. It is tolerably clear that the ejection was not spherically symmetrical, but the large radial velocities given by the *nebulosities* on Humason's plate of 1933 again indicate that the motion was not all transverse. Since for a motion of 1″.0 per annum we have the relation:

$$\cot \theta = D/0.211\, r,$$

we deduce that an angle of 22° with the line of sight would give for Nova Persei an absolute magnitude —7 at maximum.

The Crab Nebula is an interesting object because of its identification with a nova of about a thousand years ago.[14] As the nova was observed visually it must have been at least of the fourth magnitude. Therefore, if the parallax given in Table VII, IV is correct, it had an absolute magnitude at least as bright as —7 at maximum. If it was a supernova it must have been of apparent magnitude —6, and could scarcely have escaped some notice in western records. More than this cannot be said; but perhaps it is worthy of note that η Carinae seems to have been intermediate in brightness between novae and supernovae. Because of the possibility that the velocity and density of ejected material may differ in different directions, and because the measures of the diameter of the disc are difficult to make, the method just mentioned cannot be expected to do more than furnish a satisfactory check on the general scale of the nova phenomenon. That it does so merely adds to our confidence that our present picture of the nature of the nova outburst is on the right lines.

A method not dissimilar in principle connects the speed of brightening and the pre-maximum radial velocity with the initial radius and brightness, and hence with the parallax. The basic data are subject to uncertainty, but, like the previously quoted method, this one indicates that our current geometrical picture of the nova outburst is in accordance with the facts. In this manner the parallax of Nova Pictoris 1925 was calculated as 0″.0015 by Spencer Jones[15]. A slightly different theory has been developed and extensively applied by one of the writers,[16] and the resulting parallaxes, initial radii, and initial luminosities are tabulated below. The method implies that the premaximum expansion of the nova is spherically symmetrical; and this is more likely to be true than that spherical symmetry is maintained after the sudden and drastic spectroscopic developments that always take place directly after maximum light.

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[13] *See* Whipple and C. Payne-Gaposchkin, P.N.A.S., 22, 195, 1936.

[14] Lundmark, P.A.S.P., 33, 225, 1921; *see* Hubble, A.S.P. Leaflets, 1, 58, 1934.

TABLE VII, V

PARALLAXES FROM SPEED AND AMPLITUDE OF BRIGHTENING

Nova		Visual Range	Adopt. Sp.	Radii (R) Init.	Radii (R) Max.	Absolute M_{vis} Init.	Absolute M_{vis} Max.	Computed Parallax	m.e.	Time of Rise
		m m								d
N Aql	1918	—1.4-10.8	cA2	1.94	290.	0.80	—11.40	0″.0016±0″	.0008	3
N Cyg	1920	1.5-14.5	A2	0.66	264.	4.25	— 8.75	0 .0009±0	.0006	10
N Gem	1912	3.7-14.5	cA?	0.38	54.	4.88	— 5.92	0 .0012±0	.0007	1
N Her	1934	1.3-13.5	cA2	0.49	135.	4.80	— 7.41	0 .0019±0	.0006	10
N Lac	1936	1.7-14.7	A3?	0.50	200.	5.00	— 8.00	0 .0012±0	.0005	2
N Per	1901	0.0-13.0	cB8	0.36	144.	4.56	— 8.44	0 .0021±0	.0006	3
N Pic	1925	1.2-12.7	cF5	1.35	290.	3.80	— 7.70	0 .0017±0	.0010	30

The calculations that lead to Table VII, V are made on the basis of the formula:

$$R = \frac{1}{8}\,\frac{vt}{(u^{1/2}\,\gamma^{-1/2} - 1)}$$

where v is the radial velocity in kilometers per second, t the time of rise in days, u the ratio of maximal to minimal luminosity, γ the ratio of maximal to minimal surface brightness, and R the initial radius in solar units.

The method on which the preceding table is based differs from the direct methods previously described, and reposes on several assumptions, which are discussed in the paper quoted. *First,* it requires an accurate knowledge of the time of outburst—a datum never available to the desired accuracy, but known in many cases within a certain range, so that the luminosities are from this standpoint lower limits, the parallaxes upper. *Secondly*, the method requires that the velocity on the rise be known; although it has never been directly observed, it can be adopted within certain limits if the reasonable assumption be made that the velocity increases in a uniform manner between the beginning of the outburst and the maximum. If this were not the case, the pre-maximum spectra might be expected to show greater signs of disturbance than they do. In practice, a value of about half the maximal velocity has been adopted. *Thirdly*, the assumption is made that the surface brightness of so exceptional a body can be calculated from the effective temperature based on color and spectral type. This assumption is physically the least certain of the three, but it is not so drastic as the previous sentence makes it appear. What is assumed is not that the *whole spectrum* shall conform to the theoretical relation between effective temperature and surface brightness, but only that the *observed spectral* range shall so conform—a far less stringent requirement. In fact the energy distribution for several novae in the photographic region has been shown to correspond fairly closely to the spectral class simultaneously inferred from the absorption lines[17]. It must again be stressed that all these remarks apply to the pre-maximum spectrum; after the maximum the state of the star is far more complicated.

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[15] Ann.Cape Obs., 10, Part 9, 166, 1931; *see* McLaughlin, A.J., No. 991, 1936.

[16] S. Gaposchkin, H.B. 899, 901, 1935.

The absolute magnitudes of novae deduced in Table VII, V are not very different from those obtained by other methods. Nova Aquilae 1918 appears as an inordinately bright object, but this is largely a result of the high value (1400 km/sec) for the pre-maximum radial velocity.

Finally, it should be noted that the directional effects discussed when the expansion of nebular shells (post-maximum) was considered cannot be supposed to enter for the pre-maximum stages, if we keep to our present idea that the initial expansion of a nova is spherically (or at least spheroidally) symmetrical.

The applications of the methods of spectroscopic parallax to novae are of very doubtful validity. The ordinary determination of spectroscopic parallax depends on a mass-luminosity relation[18], and is therefore wholly inapplicable to a nova in the maximum state, since it is probable that the mass of a nova (if it conforms to a mass-luminosity law at all) corresponds to the minimal luminosity[19]. Therefore the spectroscopic parallaxes that have been determined cannot be considered to have proved more than that the spectra show supergiant characteristics.[20] More strictly, the evidence indicates that the surface gravity is low at the place where the line spectrum is formed; and since a nova at maximum is essentially a dwarf star with its outer atmosphere expanded linearly by perhaps two hundred fold, the spectral characteristics associated with low surface gravity should be very marked. Furthermore, the distribution of the spectral energy, especially in the unobserved and important ultraviolet regions, may deviate greatly from a black body distribution, with complex and hitherto unpredictable effects upon the line spectrum.

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[17] *See*, for example, Whipple and C. Payne-Gaposchkin, H.C. 413, 1937.

Parallaxes of novae derived from observations of interstellar matter have recently been extensively used, although their individual precision is low. The first such parallax for matter surrounding, or near, a nova, was that derived from observations of the expanding nebulous "envelope" of Nova Persei 1901, on the assumption that the observed disturbance was traveling through the nebulosity with the velocity of light. An estimate of the distance of the nova, assumed to be situated in the nebulosity, was first made by Kapteyn[21], the resulting parallax being 0″.011. It has, however, been shown by Russell[22] that the parallax thus determined may be too large or too small, according as the reflecting nebula is nearer to us or further from us than the nova. No other nova has shown a similar phenomenon, but η Carinae is seen projected upon a bright nebula, with which it is most probably associated[23], although a brightening of the nebula, resulting from the outburst of the star, does not seem in this case to have been satisfactorily demonstrated. If the star and the nebula are at the same distance, the former must have been brighter than −11 at maximum, far brighter than normal novae, but not so bright as the supernovae (unless it is assumed that η Carinae is obscured by three or four magnitudes; even so, it differs widely in other properties from all known supernovae, having at present abnormally narrow bright lines rather than abnormally wide ones.)

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[18] Russell, Dugan, and Stewart, Astronomy, 875, 1926.

[19] *See* Payne, the Stars of High Luminosity, 86, 1930. We are indebted to Professor H.N. Russell for calling our attention to this point.

[20] Lundmark, Lund Obs.Circ. 10, 1934.

[21] A.N., 157, 202, 1901.

[22] Russell, Dugan, and Stewart, Astronomy, 788, 1926.

[23] Bok, Harv.Repr. 77, 1932.

A method of determining distances of novae that has recently enjoyed considerable popularity, because of its simplicity and speed, depends on the intensity of interstellar lines. Such parallaxes have been obtained for most of the bright novae observed during the last few years, and could no doubt be similarly determined for earlier novae from existing spectra. The method is open to two disadvantages: the complex structure of the H and K lines in many novae renders it difficult to separate and estimate the intensity of the interstellar lines satisfactorily; and the strength of interstellar lines is in itself so unreliable a criterion of distance for single stars that it should probably never be used, except in obtaining approximate results, or for statistical purposes.

The general conclusions that can be drawn from all types of measures of the parallaxes of galactic novae have already been summarized. The parallaxes of Table VII, III lead to a mean absolute visual magnitude −5.88, if Nova Sagittae 1913 (*q.v.*) is omitted. The stars of Table VII, IV lead to the higher value −8.3; but if the allowances suggested in the text are made for foreshortening, these data are compatible with an absolute visual magnitude near to −7. The parallaxes of Table VII, V give the mean value −8.23. If we suppose the surface brightness to have increased during the rise, this value will diminish; and vice versa. By giving the method of direct measurement

SUMMARY OF LUMINOSITIES OF NOVAE AT MAXIMUM

Method	Mean Absolute Magnitude	Number of Novae
Direct Measure of Parallax	−5.88	9
Expanding Nebular Discs	(−8.3)	3
Speed of Rise	(−8.23)	7
Andromeda Nebula (Hubble)	−5.5	115

of trigonometric parallax twice the weight of the other two methods, and further weighting according to number of determinations, we obtain for the mean absolute visual magnitude of galactic novae at maximum a value −6.65. The novae in the Andromeda nebula, with a value −5.5 according to Hubble[24], −5.5 also according to Lundmark's rediscussion[25], cannot in our opinion be considered to differ significantly. No doubt the novae at maximum are among the most luminous of stars. At minimum they are on the average dwarfs with about the same brightness as the sun.

Nova Sagittae 1913 is apparently an exceptional case. The proper motion and parallax would lead to the conclusion that this star must have had an absolute magnitude between +3 and +4 at maximum, unless we were to assume an unreasonably high space motion[26]. We shall place it alone in the class of "subnovae," which may be supposed to fall between the novae proper and the SS Cygni stars; the latter we regard as "dwarf novae," noting that Gerasimovič[27] calls the SS Cygni stars the "subnovae," and has designated Nova Sagittae 1913 a "dwarf nova." It seems as though our notation is more logical, linking together as supernovae, novae, and subnovae the stars with similar light curves, while forming a parallel with the terms "supergiant," "giant," and "subgiant," for ordinary stars.

iv. Light Curves, Amplitudes, and Recurrence.—The light curves of novae display considerable variety. The commonest type has a very sudden rise in brightness (the whole increase occupying one or two days), a brief maximum, and a fall in brightness, which, though rapid, is slower than the rise. Nova Cygni 1920 and Nova Lacertae 1936 had light curves of this kind. Often the fall in brightness is complicated by periodic and quasi-periodic variations of considerable amplitude, the period apparently decreasing as the fluctuations die away*. Nova Persei 1901, Nova Aquilae 1918, and Nova Geminorum 1912 showed these secondary fluctuations of brightness as their magnitude fell. A second type of light curve, less common than the first, has a slower rise in brightness and probably a less regular decline—when secondary fluctuations are present they are not noticeably periodic. Light curves of this kind were shown by Nova Pictoris 1925 and Nova Aquilae 1936.6. A third sort of light curve has perhaps a rapid rise like the first, but the star remains near maximum light for a long time (three or four months). A sudden fall in brightness, reaching or nearly reaching the original magnitude of the star (at least in visual and photographic light), is followed by a gradual but steady increase to about the brightness from which the sudden drop took place; the star then gradually declines. Nova Aurigae 1891 and Nova Herculis 1934 had light curves of this type, which is apparently uncommon; possibly Nova Coronae Borealis 1866 varied in a similar way. A fourth type of light curve might be formed to include the very slowly developing novae such as η Carinae and RT Serpentis. Classifications of the light curves of novae have been formed by Gerasimovič,[28] Lundmark,[29] Loreta,[30] and Kukarkin and Parenago.[31]

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[24] Mt.W.Contr. 376, 1929.

[25] Lund Medd., No. 125, 1930.

[26] P.A.S.P., 46, 229, 1934.

[27] Pop.Astr., 44, 78, 1936; Pulk.Circ. 16, 1936.

* See, however, the analysis of the light curve of Nova Aquilae 1918, p. 258.

The amplitudes of the normal novae are considerable; because of the uncertainty of their pre-maximum minimal magnitudes and the inconsistency of the magnitude scales used by different investigators it is difficult to make a precise determination. The average amplitude is about eleven magnitudes. Thus the absolute magnitude of an average nova before the outburst is about +4.5, and these stars can therefore be regarded as true dwarf variables.

The stars Nova (T) Pyxidis 1890 and Nova (RS) Ophiuchi 1901 are both recurrent novae, the former with three recorded maxima (1890, 1902, 1920) and the latter, two (1890, 1933). Both are of smaller range than the average, having varied respectively through 7.6 and 7.5 magnitudes. A third star, regarded by Stratton[32] as possibly a recurrent nova, has been observed three times: by Hevelius[33] in 1667, by Bevis, seventy years later, and by Shackleton in 1892[34]; assuming one appearance to have been missed, the mean cycle would be seventy-five years—the longest period ever suggested for a star, whether a nova or otherwise. Nova Vulpeculae 1670, which has been identified by Steavenson[35] with a variable star of the sixteenth magnitude, is not, strictly, a recurrent nova, and was very possibly not a nova at all. The three well defined bright maxima, and the statement that the star was fluctuating considerably in brightness, suggest a peculiar red variable, perhaps of Class N; apparently this is Stratton's view.[36] Nova Aquilae 1919 had a similar history; its spectrum (Class R0), and the peculiarity of its light curve, have led us to reject it from the list of novae.

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[28] Unpublished.
[29] Pulk.Circ. 16, 1936; Pop.Astr., 44, 78, 1936.
[29] Lund Medd., Series 2, No. 74, 1935.
[30] A.N., 257, 77, 1935.
[31] Stellar Variability, Chapter 5, 1937.
[32] Handbuch d.Astrophys., 6, 525, 1928.

Two stars that are included in the list of novae have had very small amplitudes—P Cygni, which is now three magnitudes fainter than it was at maximum, and FN Sagittarii, which is included on the basis of form of light curve. Neither is a typical nova, but both are closely allied to the group. Especial mention should be made of V Sagittae, the one star (included in the list of novae) for which no maximum has been recorded. The possibility that the star may be an ex-nova has been independently suggested by Ryves[37] and by one of the writers;[38] and though Jacchia[39] considers the star more truly periodic than this suggestion would imply, the spectrum, and the irregularity of variation, recalling Nova Persei in recent years, have led us to place it with the novae.

v. Variability of Novae at Minimum.—Many, if not most, novae are known to have been slightly variable before their outburst, and almost all continue to vary slightly, at least for several decades—Nova Lacertae 1910 being a conspicuous exception. For the pre-outburst magnitude of this nova we are dependent on the examination of the old photographs, but the

[33] *See* J.B.A.A., 4, 96, 1893.
[34] *See* J.B.A.A., 4, 215, 1894.
[35] M.N., 95, 78, 1934.
[36] Handbuch d.Astrophys., 6, 252, 1928.
[37] M.N., 92, 715, 1932.
[38] Payne, H.B., 894, 1934.
[39] Bologna Publ., 3, 1, 1934.

post-maximum variations are well known, chiefly by the continuous observations of Steavenson and Peek. Data concerning the variations at minimum of ten novae are given in Table VII, VI. If V Sagittae is a true ex-nova, it adds to the list a star with a range of over three magnitudes.

TABLE VII, VI

VARIATIONS OF NOVAE AT MINIMUM

Nova	Range of Variation Pre-maximum	Post-maximum*
	m	m
Aur 1901	constant	constant
Aql 1918	1.0	0.5
Cir 1906	Small	..
CrB 1866	..	0.4
Cyg 1920	constant:	constant:
Gem 1903	2.4	Small; star fainter than before outburst
Gem 1912	constant:	constant:
Her 1934	0.4	..
Lac 1910	..	constant:
Lac 1936	0.5	..
Oph 1848	..	1.0
Oph 1901	1.0	1.0
Per 1901	1.2	1.5
Pic 1925	constant:	..
Pyx 1890	slight	slight
Sco 1906	slight	slight

* After star has returned to original brightness.

Nova Persei 1901 is the most interesting and the best-observed star in Table VII, VI; its variations are quite irregular, and if no bright maximum had occurred it would have been placed in Chapter X, with the "nebular" variables, possibly those connected with visible diffuse nebulae. From the point of view of interpretation, the affiliation of Nova Persei with nebulosity is of great importance.

vi. Spectral Characteristics of Novae.—The spectroscopic developments of novae are extremely complicated, and display such a variety of detail that not even one nova has ever been discussed completely and satisfactorily from the spectroscopic standpoint. But in general terms the process is always the same.[40]

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[40] *See* Menzel and Payne, P.N.A.S., 19, 641, 1933; Boyce, Menzel, and Payne, P.N.A.S., 19, 581, 1933; Vorontsov-Velyaminov, Rus.A.J., 14, 113, 1937.

The initial brightening is accompanied by a negative radial velocity, indicating that the surface layers of the star are approaching the observer. The spectrum, in the pre-maximum stage, is always primarily an absorption spectrum; if bright lines are present they are relatively weak, or at least not predominant,* and occur as red borders to strong absorption lines.

After the brightness of the nova has passed its maximum, the complex bright lines that are so characteristic of novae make their appearance, and rapidly attain great intensity relative to the continuous spectrum. The absorption lines maintain their individuality. The radial velocity may change, usually increasing somewhat after the maximum light, compared to its pre-maximum value. The absorption spectrum becomes very complex, and several different groups of absorption lines, differing in radial velocity and often also in excitation, are commonly observed at this stage. The spectrum now undergoes a more or less gradual development, first the absorption lines and later the bright lines changing in such a way as to indicate increasing excitation. In the spectrum of Nova Aquilae, for instance, the lines of NII, NIII, NIV, and NV appeared successively in absorption. The bright lines that first appear are those that were visible as faint red edges to absorption lines just before the maximum, but, at some time after the maximum, another group of lines—the forbidden bright lines of certain elements (notably oxygen, nitrogen, neon, and sulphur)—make their appearance, unaccompanied, of course, by corresponding absorption lines. As the spectrum develops, these forbidden lines, particularly those of OIII (4363; $4959=N_2$; $5007=N_1$), increase in strength relative to the continuous background, and in the later stages of the bright line spectra of most novae the two latter, and the HeII line 4686, are the chief features.

Almost all descriptions of the spectral development of novae refer to large changes (usually increases) of brightness of the emission lines. It must be emphasized that when observations of such changes are based on eye estimates of intensity relative to the continuous background they have little meaning, since the continuous background (which represents, roughly speaking, the intensity of the nova itself, freed from the additional light contributed by the bright lines, both quantities, of course, measured only over the relatively small range of wave-lengths accessible to observation), is varying too. That the continuous background may be fluctuating considerably, even though the whole observed light of the nova, including that of the more intense and less variable bright lines, is relatively constant, has been shown for Nova Pictoris[40a] and Nova Aquilae.[40b] Measures of the true intensity of bright lines for several novae have been carried out recently at Harvard and elsewhere.[40c]

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* Pre-maximum spectra of novae are seldom obtained more than a couple of days before, and therefore only a few magnitudes below, the maximum. For Nova Herculis (*q.v.*) the bright lines were very strong on the day of discovery. Very possibly the *early* pre-maximum spectrum of a nova may have powerful bright lines. Whether the forbidden lines ever appear before the maximum is an important, unanswered question.

The spectra of such novae as have been observed before maximum brightness have all been of comparatively early spectral class. Unfortunately there is seldom detailed information long before maximum, and no good spectral observations exist for a pre-maximum nova more than three magnitudes below its maximum—so that seventy-five per cent of the rise is spectroscopically unknown. The better observed pre-maximum spectra are summarized in Table VII, VII.

TABLE VII, VII

PRE-MAXIMUM SPECTRA OF NOVAE

Nova	Spectrum	Remarks
Aql 1918	cA2qα	Before outburst, spectrum of no definite type, but resembling Class A *in distribution of continuous radiation* (H.A., 81, 180, 1920). See p. 258.
Cyg 1920	cA2q	
Her 1934	cB-cAq	
Lac 1936	cA2 q	
Per 1901	B8eq	Intensities of lines abnormal for B8; no spectral class is closely represented; lines hazy; the earliest recorded nova spectral type.
Pic 1925	cF5q	Supergiant characteristics.

It would be impossible to give a general description of the spectral developments that succeed maximum brightness; some typical examples are discussed in the section devoted to individual stars.

[40a] Payne-Gaposchkin and Menzel, H.C. 428, 1938.

[40b] Menzel and Payne-Gaposchkin, unpublished.

[40c] Whipple and Payne-Gaposchkin, H.C. 414, 1937; Payne-Gaposchkin and Menzel, *op. cit.*

The spectra of novae after they have returned to their original brightness are usually somewhat featureless, sometimes showing weak Wolf-Rayet bands, and give, in general, the same impression as the spectra of the nuclei of planetary nebulae. Although the stellar spectrum does not usually, according to Stratton,[41] retain the nebular bands more than about nine years, the star is still able to excite these bands in the nebulosity that it has emitted, if the spectrum of Nova Persei 1901, thirty-three years after its outburst, can be regarded as typical.[42] Probably no real distinction can be drawn between the stellar and nebular spectra of a nova, which may continue for many years to excite faint nebular light in the envelope with which it has surrounded itself.

A nova that stands out as having a post-maximum spectrum of Class M, with wide bright bands of hydrogen and helium and possibly nebular lines, is Nova Coronae Borealis 1866. It is one of the novae in very high galactic latitude, and might conceivably be considered a supernova.[43]

The spectra of novae before the beginning of the outburst are completely unknown except for the somewhat indefinite observations[44] of Nova Aquilae 1918. On the whole the data seem to justify the opinion that a nova returns gradually to the same spectrum, as it does to the same brightness, that it had before the outburst. The bright maximum, though conspicuous, is the embodiment of a superficial phenomenon, for only a very small fraction of the mass and volume of the nova is permanently affected by it. The observed fact that one nova can undergo the same process two or three times speaks against the occurrence of a fundamental alteration in the star as a consequence of, or as a cause for, the outburst of light. We should note that this is not necessarily true of the supernovae; but as yet we do not know enough about these objects to be able to state that it is definitely untrue.

[41] Handbuch der Astrophys., 6, 284, 1928.

[42] Humason, P.A.S.P., 46, 229, 1934.

[43] *See* p. 261.

[44] *See* p. 258.

vii. Continuous Energy Distribution.—The distribution of energy in the continuous spectrum of a nova has for the first time been carefully observed for the early post-maximum stages of Nova Herculis 1934[45] and Nova Lacertae 1936.[46] The distribution of energy deviates definitely from that for a black body, and in particular there is a large excess of energy in the ultraviolet. It has been shown at Harvard[47] that the energy distribution for Nova Herculis, and its change with the apparent magnitude of the star, are in harmony with the idea that Nova Herculis is surrounded by a continuously expanding envelope. The changes in the energy distribution for Nova Lacertae 1936 appear to follow the same relationship.

If there are appreciable deviations from black body distribution, the color indices of novae, as usually obtained by the difference between photographic and visual magnitudes, must be interpreted with care, even for times when the effect of bright lines on the color is not large. At any time after maximum, the bright lines rather than the bands govern the apparent color and determine the color index; soon after the maximum the effect of strong bright Hα will make a nova seem reddish; and in the later stages a greenish color will be given by the [OIII] lines N_1 and N_2, the [NeIII] lines, if they are strong, contributing sensibly to the photographic magnitude (they are too far to the violet to be observed visually), as does the ultraviolet excess. Such effects no doubt produce the remarkable negative color indices observed, for example, by Himpel[48] for Nova Herculis.

viii. Observations of Nebulous Envelopes.—A number of novae have been found, after a considerable interval following maximum, to be surrounded by nebulous envelopes, of such size and motion as to suggest that they are the actual masses of gas whose ejection accompanied the maximum. Nova Persei 1901, the best-observed star in this regard, was first shown in 1916 to be associated with faint nebulosity; the growth of the nebulosity is described and illustrated by Stratton[49] on the basis of the observations of Barnard and Aitken, the direct photographs of Ritchey and Humason, and the spectra taken by Humason. The expanding disc around Nova Aquilae 1918, likewise first seen by Barnard, was later photographed by Hubble and Duncan.[50] Several other novae, though not showing nebular discs, were remarked visually to show hazy images (Nova Cygni 1876, Nova Aurigae 1891, and Nova Sagittarii 1898).

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[45] Beileke and Hachenberg, Zts.f.Ap., 10, 366, 1935; Whipple and C. Payne-Gaposchkin, H.C. 412, 1936; Oehler, Zts.f.Ap., 12, 281, 1936.

[46] Petrie, Publ. Amer. Astr. Soc., 8, 252, 1936.

[47] Whipple and C. Payne-Gaposchkin, H.C. 413, 1936.

[48] A.N., 257, 169, 1935.

[49] Handbuch d.Ap., 7, 683, 1936.

A different phenomenon—superficially at least—the actual division into components, has been observed for three novae. The nucleus of η Carinae is hazy and has probably become multiple.[51] Nova Pictoris 1925 had a definitely multiple nucleus consisting of four unequal components,[52] which increased in separation with the passage of time. Nova Herculis 1934 was found by Kuiper[53] to be double, and the separation of the components has increased continuously. Lastly, the nucleus of the Crab Nebula, surrounded by expanding nebulosity that is almost certainly the remains of the outburst of a nova some centuries ago,[54] is double,[55] though in this case there is no evidence that the apparent double nucleus is the remains of the original nova, or the source of the nebulosity.

ix. Relation of Novae to Planetary Nebulae.—The novae after their decline in brightness are indistinguishable, in all essential properties, from the nuclei of planetary nebulae.[56] If the earlier history of Nova Persei 1901 were unknown, its spectrum, as photographed by Humason,[57] would place it definitely with the planetaries. The same might be said of the instantaneous spectrum of almost any nova in the "nebular stage."

In galactic distribution the planetary nebulae are very similar to novae, as may be seen from Table VII, VIII. The data for the planetary nebulae are taken from Vorontsov-Velyaminov's book[58]; those for galactic novae, from Table VII, I (rejected novae omitted).

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[50] Mt.W.Contr. 335, 1927.

[51] van den Bos, M.N., 92, 19, 1931; Stratton, Handbuch d.Ap., 7, 681, 1936.

[52] *See* Spencer Jones, Ann. Cape Obs., 10, No. 9, 1931.

[53] P.A.S.P., 47, 228, 1935.

[54] Duncan P.N.A.S., 7, 179, 1921; Mayall, P.A.S.P., 49, 101, 1937.

[55] Stratton, Handbuch d.Ap., 7, 682, 1936.

[56] Vorontsov-Velyaminov, New Stars and Galactic Nebulae, 210, 1935; *see also* Zts.f.Ap., 8, 195, 1934.

[57] P.A.S.P., 46, 229, 1934; *see* Handbuch d.Ap., 7, 683, 1936.

[58] New Stars and Galactic Nebulae, p. 304, 1935.

TABLE VII, VIII

NOVAE AND PLANETARY NEBULAE: DISTRIBUTION IN GALACTIC LONGITUDE

Galactic Longitude:	0-44	45-89	90-134	135-179	180-224	225-269	270-314	315-359
Novae	16	5	5	8	2	7	7	40
Planetary Nebulae	28	19	10	6	6	12	21	30

The absolute and apparent magnitudes of the nuclei of the planetary nebulae and the novae at minimum are about the same, and therefore their spatial distributions must be similar. It would be easy to jump to the conclusion that planetary nebulae are the remains of old novae, but a little consideration will show that this view is untenable, at least without qualification. First, there are but 150 known planetary nebulae; far too few, if we consider, following Bailey,[59] that the number of novae brighter than the sixth magnitude at maximum (or the sixteenth at minimum) is one or two a year, and that five novae of the second magnitude or brighter have occurred since 1900. Secondly, though the characteristic form of the lines in the spectra of planetary nebulae has been shown by Zanstra[60] to be best interpreted in terms of expansion of the nebular "shells," the velocities are of the order of only twenty kilometers a second. The ejection velocities for most novae are of the order of five hundred to a thousand kilometers a second; and the present radial velocity of the nebulosity surrounding Nova Persei 1901 confirms the reasonable expectation that these velocities will be essentially preserved, once the matter has escaped from the gravitational field of the star (which it does during the first few days of a nova outburst). Thus the observed radial velocities of the envelopes of planetary nebulae are too small to be associated with normal novae. There are, however, some novae that increase in brightness very slowly, and from the observed correlations between rate of increase of light and radial velocity of expansion, it may be expected that such novae (of which Nova Sagittarii 1912 and 1914, and possibly RT Serpentis,[61] are examples) would give radial velocities of the same order as are observed in the spectra of the planetaries. The nebulosity surrounding the novae that expand with large velocities probably does not remain luminous to large enough angular distances to be visible as a disc, save in rare cases like Nova Persei 1901 and Nova Aquilae 1918; and it seems probable that these nebulosities also will cease to be visible within a finite time. The "slow novae" are rare enough to meet the difficulty that planetary nebulae must not be supplied at too great a rate; and may tentatively be regarded as their source.

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[59] P.A.S.P., 24, 554, 1921.

[60] M.N., 93, 131, 1932; see also Perrine, A.N., 237, 89, 1929.

[61] *See* p. 264.

The planetary nebulae are probably to be regarded as essentially temporary objects. Without any implications as to their source, Whipple[62] has calculated an average of 3×10^4 years from the measured radial velocities of expansion, diameters, and distances of 24 planetary nebulae. Similar results were obtained by Vorontsov-Velyaminov[63] on different, simpler assumptions, and with fewer data.

41. Observations of Individual Novae.—The variety of properties that may be exhibited by novae is best illustrated by brief summaries of the behavior of individuals. A number of novae have therefore been selected, as representing the types of behavior that are encountered among these objects. Six of the normal novae are of the more or less common types; two are recurrent, and four are of more or less uncommon types, though perhaps it would be incorrect to call them abnormal, since no nova can be regarded as displaying strictly normal behavior, and, like the Wolf-Rayet stars, they are all different.* The light curves of a number of novae[64] are reproduced in Figure IX, I.

Nova Cygni 1920.—Campbell has published a light curve of Nova Cygni 1920 during the first few months following its outburst, compiled from the principal sources of visual observations.[65] It shows a rapid rise in brightness, and a rather less rapid decline. Nova Cygni is a good example of a rapidly developing, uncomplicated nova; the light curve showed few irregularities after the maximum, and the spectral development was smooth. The bright lines were clearly cut and comparatively narrow, and showed no very conspicuous structure. No direct observation has been made of nebulosity ejected from the star, nor has any peculiarity, such as duplicity, been hitherto noted in its image.

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[62] H.B. 908, 1938.

[63] New Stars and Galactic Nebulae, 296, 1935.

* The parallel with the Wolf-Rayet stars is, indeed, a very close one. The Wolf-Rayet stars may be regarded as novae that are permanently at maximum, and when one of them is variable, we have little hesitation in suggesting that it is an ex-nova—witness V Sagittae.

[64] Kindly given by Campbell from unpublished data at Harvard.

[65] L. Campbell, H.B. 890, 1933.

Nova Persei 1901.—The nova that has been observed most fully, and from the most aspects, is Nova Persei 1901. It was the first nova for which a pre-maximum spectrum was photographed[66]; and, besides the usual studies of radial velocities of absorption lines and the intensities of bright lines, it furnished observations of what now appears to have been the spreading of its maximum light through surrounding nebulosity[67]; later, the nebulosity spreading from the star was itself photographed[68]; and, still later, not only could the nebulosity still be photographed and its motion directly determined, but also the spectra of original star and ejected nebulosity could be photographed and distinguished,[69] and the distribution of ejected material thus studied. Furthermore, the pre-maximum fluctuations of Nova Persei 1901 have been traced from the photographic records, and the post-maximum changes, which are as marked as those for any recent nova, are well known from the continued studies of Steavenson[70] and of Peek.[71] Nova Persei, taken in conjunction with Nova Aquilae 1918 and Nova Herculis 1934, provides us with our best material for a broad view of the general nature and progress of the nova phenomenon.

To describe the development of Nova Persei in great detail would be out of place in a general account of novae. It is, however, in some respects a limiting case. It showed a pre-maximum spectrum of the earliest spectral class that has been reported; classified at the time as B8, it is not accurately assignable to any class, for the wide, hazy, apparently asymmetrical absorption lines are of abnormal intensity, MgII and AlII being unusually prominent. If anything, the spectrum points to an ionization higher than that for a star of Class B8.

The bright line spectrum, also, had several uncommon features. The lines showed less structure than those, for instance, of Nova Aquilae. Their intensities were, and still are, unusual: the bright lines of [NeIII] soon became the most conspicuous feature of the spectrum of the nova,[72] and still are the strongest lines in the spectrum of the ejected nebula. The bright line of [NeIV] was also of unusual prominence.[72] Whether these conspicuous appearances are the result of an unusual abundance of neon, or of special conditions of excitation, are problems for future study. Nova Sagittarii 1936 also showed the lines of [NeIII] with unusual intensity.[73]

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[66] Miss Cannon tell us that so surprising did it appear to the Harvard spectroscopic workers when the first spectrum taken of Nova Persei 1901 proved to be almost entirely an absorption spectrum, that they at first supposed, erroneously, that the wrong star had been photographed.

[67] Kapteyn, A.N., 157, 202, 1901; *see* Russell, Dugan, and Stewart, Astronomy, 788, 1926.

[68] Ritchey, *see* Handbuch d.Ap., 7, 683, 1936.

[69] Humason, P.A.S.P., 46, 229, 1934.

[70] M.N., observations published annually.

[71] M.N., observations published annually.

[72] Boyce, Menzel, and Payne, P.N.A.S., 19, 581, 1933.

[73] Miss Cannon, H.B., 907, 1937.

The spectrum of the central star, now distinguishable from that of the nebula, is characteristic of a bright line O star, which shows the lines of hydrogen and ionized helium, but no forbidden lines. The central star is evidently competent to produce the excitation now observable in the nebular envelope. It is still varying irregularly, with an amplitude greater than a magnitude, and is thus one of the very few intrinsically variable O stars known.* The spectrum of the nebula shows that the ejection was more powerful (as judged from intensity of bright lines) on one side of the star, and that the principal motion of the ejected nebulosity was across the line of sight. The maximum radial velocity in the line of sight is still approximately the same as that attained by the absorption lines at the time of maximum; and this is not surprising, for the material must have left the gravitational field of the star within a few hours.

The light curve of Nova Persei shows a very rapid rise in brightness, and also large and rapid post-maximum fluctuations, which were better shown by this nova than by any other. They display a continually decreasing period and amplitude, and suggest gravitationally governed oscillations; their origin is, however, probably more complex, as will appear by analogy with the post-maximum behavior of Nova Aquilae 1918. Oscillations of a semi-periodic nature after the maximum are found in the light curves of many novae, but they are not invariably present; the slower novae, such as Nova Pictoris 1925 and Nova Herculis 1934, did not display them; neither did the rapidly developing Nova Cygni 1920.

Nova Aquilae 1918.—The rapid development of Nova Aquilae, its great range, and its conspicuous post-maximum fluctuations, rendered its light curve very distinctive. Its spectroscopic development was marked by very high velocities, and by remarkable changes in the contours of the bright lines. The post-maximum fluctuations were of longer period and smaller amplitude than those of Nova Persei 1901, but resembled the latter in the simultaneous falling off of period and amplitude. The fact that these post-maximum fluctuations were intimately connected with the contours of the bright lines (which dipped in the center during the minima of the light curve)[74] seems to indicate that the fluctuations themselves were not simply caused by oscillations of the "surface" of the nova, but were rather closely bound up with the ejection process that was feeding the bright lines.[75]

After the semi-periodic post-maximum fluctuations had ceased, the contours of the bright lines assumed the saddle-shaped form that characterized them for some time later.[76] It is clear that the ejected material had axial symmetry, with the axis nearly in the line of sight. The nebular disc later photographed at Mount Wilson[77] is very different from that shown by Nova Persei, where the ejected material was moving across the line of sight.

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* BM Orionis (see Chapter XI) is not an O star, but a B star, according to the Mount Wilson investigators. We regard V Sagittae as a possible ex-nova (see Table VII, I); the star H.D. 41566 is of unknown antecedents, though its spectrum is known to vary, and its brightness suspected to do so (C. Anger Rieke, H.B. 891, 1933). The nucleus of N.G.C. 7662 was suspected by Barnard to be variable, but no further observations have been reported of what would have been an important and significant phenomenon. We know little, also, of Y Coronae Austrinae. Both it and H.D. 41566 (which is in Monoceros) may possibly qualify as nebular variables.

[74] Menzel and Payne, P.N.A.S., 19, 641, 1933.

[75] *See* Whipple and Payne-Gaposchkin, H.C. 413, 1936.

[76] Menzel and Payne, *op. cit.*

A spectrophotometric study of the spectral development of Nova Aquilae, now being carried out by Menzel and one of the writers, shows that the fluctuations that began soon after the maximum did not die out as soon as the visual light curve (based on an integration of the visible light of the nova) would lead us to expect. When the intensity of the original star (continuous background) is separated from the effects of the bright lines, it appears that the star itself continues to fluctuate for some time after the oscillations die out in the integrated light. The bright lines do not fluctuate as much as the continuous background, and their changes of brightness lag somewhat behind those of the star that is exciting them. As the period of the fluctuations of the star becomes shorter, the lag obliterates more and more the effects of its changes of brightness.

This phenomenon is not confined to Nova Aquilae; it is observed for Nova Pictoris (*q.v.*), and is probably present for all novae to some extent, but more particularly for those that undergo large post-maximum fluctuations.

Nova Aquilae 1918 is the only nova hitherto known for which the pre-outburst spectrum has been observed. The description is quoted in full, for it has often been misquoted and the statement made that this nova was of Class A before the outburst: "The spectrum appears to be nearly continuous, perhaps due to faintness. Several dark lines are, however, barely seen, which appear to belong to the hydrogen series. In the distribution of light, the spectrum resembles those of Classes B and A. While the spectrum cannot be classified, it is safe to say that it was not of Class G or K, but was near Class A" (Miss Cannon, H.A., 81, 180, 1920).

Nova Aurigae 1891.—The available observations of Nova Aurigae are very inadequate when compared with those of more recent novae, but the star is of great importance to the student of novae. At the time of its appearance its significance lay in its unique light curve—a fairly rapid rise, a protracted maximum, a sharp fall in brightness, and a subsequent slow rise and final decline. At present it is even more important that another star, Nova Herculis 1934, has duplicated the "unique" light curve in detail; and moreover, so far as the records can be used, the duplication extends to details of spectroscopic behavior.* Nova Aurigae was not found to display, like Nova Herculis, duplicity after the decline in brightness; but as it is not yet known how long the apparent duplicity of Nova Herculis will persist, we cannot be sure that this feature was not missed for Nova Aurigae.

Like Nova Herculis, Nova Aurigae displayed relatively low excitation before the great minimum, the only forbidden lines present being those of [Fe II].† After the second rise in brightness, however, the lines of [O III] and [NeIII] made their appearances, as was also the case for Nova Herculis.

[77] Hubble and Duncan, Mt. W. Contr. 335, 1927.

* An unpublished study of the records of Nova Aurigae 1892 by Miss Hoffleit, kindly made available to the writers, reaches this conclusion.

† Only three "normal" novae have hitherto shown the forbidden lines of ionized iron—Nova Aurigae 1891, Nova Pictoris 1925, and Nova Herculis 1934; all are of the "slow" type, which is apparently necessary for the production of these particular lines (see Menzel and Payne, P.N.A.S., 19,

Nova Herculis 1934.—

Two new observational points are contributed by Nova Herculis, and both have an important bearing upon theory. The first is the deceleration in the radial velocity, deduced from the absorption lines[78] before the maximum. We raise the question as to the possible effect of the emission on the red edge of the lines before maximum upon the measured radial velocities. Pre-maximum spectra have been obtained for a number of novae, notably Nova Pictoris 1925 and Nova Herculis 1934. In all cases there have been considerable emission components on the red edge of the absorption lines, which have become progressively fainter as maximum is approached, and at maximum have commonly become so weak as to be difficult to observe. This phenomenon is strikingly illustrated by the Harvard spectrograms of Nova Pictoris 1925; and without making any assumptions as to its cause, it is easy to see that it would have the effect of shifting the "centers" of the absorption lines progressively toward the red as maximum is approached, and would thus tend to reduce the negative velocities, giving an impression of a deceleration. It cannot be asserted that the whole effect observed is due to this cause; but until its probable size is evaluated, the reality and size of the deceleration must itself remain uncertain.

The second important observation concerning Nova Herculis was the discovery of its apparent duplicity.[79] The two bodies, which appear to be separating with uniform velocity, were only observed, and probably only observable, after the great minimum. Their nature will be more thoroughly understood when they have travelled far enough apart for their spectra to be separately examined. So far as we can tell at present, they are not stellar bodies, but nebular masses, and the original star from which they were ejected probably lies between them, although at present (1937) they are too near together and too bright for it to be discernible.[80] Its presence is probably shown in the integrated spectrum of the nova by a continuous background appropriate to a tenth or eleventh magnitude star.[81] In any case, it would not be justifiable to infer from the observations of Nova Herculis, just described, that the nova phenomenon is essentially a double-star one.*

641, 1933). These [Fe II] lines are also shown by the spectra of the "abnormally slow" novae, η Carinae (see p. 265) and Nova (RT) Serpentis 1909 (see p. 264). The small-range "novae," P Cygni and AG Pegasi, (see p. 266) show them also. Throughout the book will be found references to other types of stars that show the [Fe II] lines: long period variables (p. 122); irregular variables (p. 311); even eclipsing stars, such as W Serpentis (p. 88), and VV Cephei (p. 86).

[78] Adams and Joy, P.A.S.P., 47, 206, 1935; *see* Russell, P.A.S.P., 48, 29, 1936; Stratton, Observatory, 59, 325, 1937.

[79] Kuiper, P.A.S.P., 47, 228, 1935.

[80] Whipple and C. Payne-Gaposchkin, P.N.A.S., 22, 195, 1936.

[81] Unpublished Harvard observations.

* The other observation that has seemed to lend color to this idea is the apparent duplicity of the nucleus of the Crab Nebula. But we have no definite knowledge that both, or either, of these stars is the original star from which the nebulosity was ejected (see p. 238). That such a star must

still exist (so that the idea of complete annihilation for the nucleus of the Crab Nebula must be abandoned), is shown by the fact that the nebula is still being excited. The "filamentary nebula" in Cygnus (N.G.C. 6960, 6992), which strongly suggests an origin like that of the Crab Nebula, is well known to have no recognizable nucleus; but here, again, we may feel certain that an exciting star, of the requisite luminosity and temperature, does exist.

Nova Pictoris 1925.—The five novae hitherto discussed were marked by relatively rapid changes, although the last two had protracted maxima, and showed, on the whole, smaller radial velocities, narrower bright lines, and altogether more leisurely behavior, than the first three. Nova Pictoris showed an even slower development, and far smaller radial velocities and narrower bright lines. It is, in many ways, the best-investigated of all the novae, and Spencer Jones' monographic studies should provide ample basis for a theoretical study of many aspects of the nova phenomenon.[82]

The rise in brightness seems to have been very slow, unless an unobserved bright maximum took place between the first and second recorded observations, which seems unlikely—the spectrum, during the first few weeks of observation, was very definitely of pre-maximum type. As with many of the "slow novae," the spectral class at maximum (cF5) was later than for those that develop more rapidly.* The light curve showed post-maximum fluctuations that gave no sign of periodicity.

The two important contributions to the observation of the nova phenomenon that were made by Nova Pictoris were the division into nebulous components, and the occurrence of the forbidden lines of [FeII]. The absorption spectra furnish a mass of data on the complexity of the radial velocity changes in the atmosphere of a nova; and an attempt to study the theory of these changes should in all probability begin with this nova. The bright-line spectrum, also, presents unusual opportunities, for the lines are narrow and well defined (due to the relatively small radial velocity), and a number of interesting unidentified bright lines would repay the study of the working physicist. A study of the intensities of the bright lines has recently been completed.[83]

Nova (RS) Ophiuchi 1901, 1933.—The light curve of one of the two well-observed recurrent novae is shown in Figure VII, 1. Apart from its rather small range, and its persistent variability at minimum (in which it is indeed paralleled by several other novae), there was nothing to set it apart from other novae before its second maximum. In light curve and in spectrum it is, in the main, quite typical. It has shown at the second maximum one feature that may set it apart from other novae—the "coronal line," at present of unknown orign, at 5303 A was found in its spectrum[84]; but it is not quite certain that this line was not present in the spectra of some other novae.

Nova (T) Pyxidis 1890, 1919.—Another recurrent nova, T Pyxidis, is of rather shorter cycle. It will be important to observe at what intervals future recurrences, if any, take place, and the star should therefore be watched for as long as possible every year. We may note that somewhat slender information concerning the spectrum at the outburst of 1919 shows it to be quite typical of a nova.[86] Like Nova Ophiuchi 1901 it has a small range; this fact has been used by Kukarkin and Parenago[87] in linking the novae and the SS Cygni stars.

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[82] Ann. Cape Obs., 10, Part 9, 1931; M.N., 94, 35, 1933; 94, 816, 1934.

* Compare however the maximal spectrum of RT Serpentis (cA8).

[83] C. Payne-Gaposchkin and Menzel, H.C. 428, 1938.

[84] Adams and Joy, P.A.S.P., 45, 301.

Nova (T) Coronae Borealis 1866.—Although modern methods of photographic spectroscopy were not in use at the time of appearance of Nova Coronae Borealis 1866, the star shows such important peculiarities that it seems worth while to deduce everything possible from the contemporary visual observations.

The light curve, compiled from various sources, is given by Campbell and Shapley.[88] The star brightened very suddenly, and after the maximum its light fell off by six magnitudes in twelve days. At maximum it was of the second magnitude, but one month later it had fallen to $9^m.5$; later it increased slightly in brightness, and remained brighter than the eighth magnitude for over a month.

Long after the maximum, changes of brightness were still noted; for example, Miss Walker[89] found photographically a slight minimum in 1905; constant brightness ($11^m.4$) during 1908 and 1909, another minimum in 1910, and a slight diminution of light in the years following 1914. Steavenson,[90] however, has noted no variation visually for a number of years.

Observations of the spectrum fall into two groups: visual observations made at the time of maximum; and recent photographic observations of the star in its present condition. Visual observations at maximum are recorded by Huggins and Miller,[91] by Stone and Carpenter,[92] and by Wolf and Rayet.[93] Their observations, some of them merely qualitative, were discussed by Vogel[94] some years later, and by Lockyer[95] at an even later date. Both conclude that the lines seen by the early visual observers were bright lines of hydrogen and ionized helium. The line seen at 501 by Stone and Carpenter was probably one of the ionized iron lines that are usually conspicuous just after maximum. Vogel's identifications (467, 463) probably correspond to 4640, 4686; but if Lockyer's identification is correct, we must identify the lines he suggests (468, 473) with 4686 HeII and 4725 [Ne IV]; the former's identifications seem the more probable, as is also concluded by Vorontsov-Velyaminov.[96] Huggins expressed the opinion that the spectrum showed some similarities with that of Betelgeuse, an interesting observation in view of more recent spectroscopic data.

The second group of spectroscopic observations, made since the star declined in brightness, all lead to the conclusion that it is now, and has been

[86] Adams and Joy, Pop. Astr., **28**, 514, 1920.
[87] N.N.V.S., **4**, 251, 1934.
[88] H.C. 247, 1924.
[89] H.A., **84**, 151, 1920.
[90] M.N., **95**, 640, 1935.
[91] M.N., **26**, 275, 297, 1866; Proc. Roy. Soc., **15**, 146, 1866.
[92] M.N., **26**, 292, 1866.
[93] C.R., **62**, 1108, 1866.
[94] Berlin Monatsberichte, 242, 1877; 304, 1878.
[95] Phil. Trans. Roy. Soc., **182**, 397, 1890.
[96] R.A.J., **14**, 113, 1937.

for many years, a red star. In 1878 Vogel remarked that an observation, made on March 28 of that year, showed a continuous spectrum, not markedly different from the spectra of other stars. Unfortunately he did not mention the color. In 1894 Espin[97] noted that the star seemed reddish, with bright and dark intervals (well seen in the violet), and possibly bright Hγ. He assigned the star definiely to Type III (Class M).* Miss Cannon,[98] on April 22, 1914, finds a spectrum of Class K0, without any bright lines. In 1921 Lundmark[99] found the spectrum to be of Class Ma with numerous bright lines, some of which were possibly only the heads of bands, but some, such as 4686 HeII, were undoubtedly genuine. In the same year Adams and Joy[100] obtained spectra which showed bright hydrogen and 4686 lines. In 1932 Berman[101] obtained a spectrum which showed bright Hβ, but no other bright lines; he classified it as of Class gM3.

Berman, in the paper just referred to, suggested that Nova Coronae Borealis 1866 may in reality be a double object, consisting of a red giant star and a blue companion that is responsible for the nova outburst. The similarity of the suggested system to that of Z Andromedae makes Berman's suggestion both interesting and probable. No other ex-nova is known that shows a spectrum of Class M; all the others that are bright enough to be examined have spectra of very high temperature and excitation, a condition which the possession of bright 4686 suggests also for T Coronae Borealis. If an absolute maximal magnitude of —7 (visual) is adopted for the star, the red companion should have an absolute visual magnitude about zero, not unreasonable for a giant M star. It is hard to imagine a giant M star brightening at the rate shown by Nova Coronae Borealis in 1866. Moreover, it is usual for rapid novae to display large ranges, but the range of Nova Coronae Borealis (if reckoned from the present brightness of the observed M star) is smaller than the average. If, however, a fainter blue star, rather than the red one, became of the second magnitude, the range may have been anything over eleven magnitudes.

A strict parallel is furnished by the recently discovered Nova Sagittarii 1936.32. Discovered at Mount Wilson by Miss Burwell, from its peculiar spectrum, the star showed the small apparent amplitude of about six magnitudes, and, before the maximum, was represented by a star of Class K. The small amplitude, the abrupt rise from the twelfth magnitude, and the equally abrupt resumption of the twelfth magnitude after the maximum, furnish rather convincing evidence that the K star is actually a nearby object and not the source of the nova outburst. The odd spectrum adds weight to this idea.[102]

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[97] A.N., 134, 123, 1894.

* Espin and others have referred to an article of a popular nature by Lockyer (The Nineteenth Century, 785, 1889) in which he is alleged to have assigned a *nebular* spectrum to T Coronae Borealis; but so far as the present writers can understand, the nova there referred to is Nova Cygni 1876: "Suddenly in that part of the heavens a third magnitude star (Nova Cygni) blazed out. This took a very considerable time to die down, as compared to the first star, in Corona, and ultimately it got down to the tenth magnitude, and now telescopically it appears as a nebula".

[98] H.A., 96, 229, 1921.

[99] P.A.S.P., 33, 271, 1921.

[100] Mt. W. Rep. 1921, p. 230, 274; *ib.*, 1922, p. 234; P.A.S.P., 33, 263, 1921.

[101] P.A.S.P., 44, 318, 1932.

A parallel with Z Andromedae is furnished by the possibility that the outburst of 1866 was not the only one that the star has undergone, though apparently it was the brightest. Herschel, as reported by Huggins and Miller,[103] recorded a sixth magnitude star near the same position on June 9, 1842. The small changes of brightness noted photographically by Miss Walker in 1909-1914 may be records of the changes of the suggested bluer star, which would be relatively one and a half magnitudes brighter photographically than the red one; similar changes would not be detectable visually, and possibly the constancy of brightness noted visually by Steavenson may arise from this cause.

If, as suggested by Berman, Nova Coronae Borealis 1866 is really a double system, it falls into line with some other novae instead of standing out as an anomalous object. The mean visual light curve, rectified for the presence of a companion of apparent magnitude 10.0, bears a strong resemblance to the light curves of Nova Aurigae 1892 and Nova Herculis 1934. It seems that all trace of nebular spectrum has long since disappeared

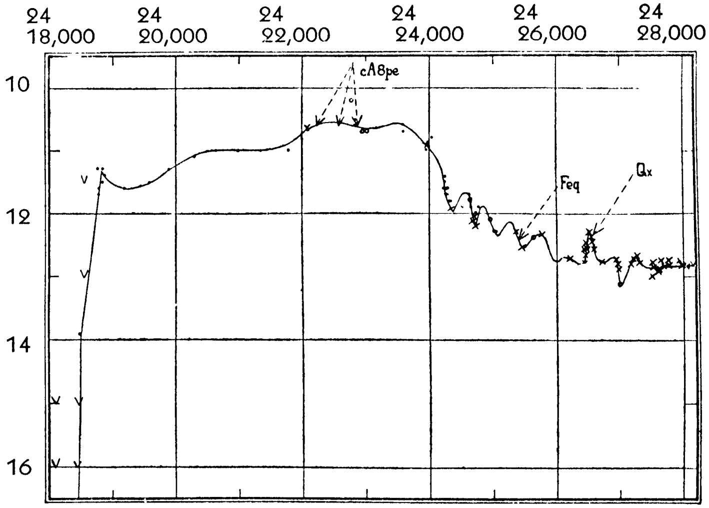

Figure VII, 2.—Light curve of Nova (RT) Serpentis 1909. Dots represent published photographic observations (Shapley, P.A.S.P., 31, 230, 1919; Bailey, H.B. 753, 1921; Shapley, H.B. 789, 1923). Circles represent published visual observations, as follows: (Graff, B.Z., p. 55, 1921; *ib.*, No. 25, 1922; *ib.*, No. 12, 1927; Lacchini, B.Z., p. 59, 1921; *ib.*, No. 5, 1929; A.N., 248, 366, 1933). Crosses represent unpublished Harvard observations. The arrows refer to points on the light curve at which spectroscopic observations have been made.

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[102] R. B. Jones, H.B. 907, 1938.

[103] M.N., 26, 275, 297, 1866.

from the light of Nova Coronae Borealis 1866*; but Barnard saw the star associated with a small nebula, without a nucleus, of the fourteenth or fifteenth magnitude.[104] The star should be watched for variations, preferably by photographic methods. That it will prove to be a recurrent nova is not impossible.

Nova (RT) Serpentis 1909.—That the nova process can be carried on very slowly, though in essentially typical fashion, is illustrated by the well-observed variations of RT Serpentis, which must now be definitely counted among the novae. Discovered independently by Wolf[105] and Barnard,[106] it has been studied, principally by photographic methods, during the intervening thirty years. The light curve is shown in Figure VII, 2, the sources of the magnitudes being given in the legend. Soon after its discovery Shapley[107] called attention to its close affiliation with the novae, a conclusion that has been substantiated by all subsequent observations.

Little need be added to the plotted light curve in describing the variations of brightness. There is a possible indication of post-maximum fluctuations of brightness—a not uncommon phenomenon among novae, as will be recalled by reference to the data on Nova Persei 1901 and Nova Aquilae 1918.

It is the spectral variation that distinguishes the star as a true nova. The five points (a,b,c,d,e) marked on the light curve refer to the Mount Wilson spectroscopic observations enumerated below.

(a) Spectra of 1919 show very few lines. Hβ and Hγ are barely visible as narrow absorption lines. Their weakness is probably a result of partial emission; 4481 (MgII) is a good line, FeII lines are dark and measurable.

(b) In 1920, Hβ was a weak emission line, Hγ showed slight absorption. The enhanced lines were more numerous and more easily seen than in 1919.

(c) In 1921, the hydrogen lines were better marked; Hβ was greatly increased in strength, Hγ neutral, Hδ in strong absorption.

Summarizing the three preceding spectral stages, Adams and Joy[108] considered that the designation A8p described the spectrum fairly well. It showed evidences of high luminosity, though the absolute magnitude was necessarily uncertain. All these descriptions are normal for the pre-maximum stage of novae.

(d) In 1928, the spectrum had undergone a great change; the continuous spectrum was almost invisible, and the strong bright lines of [FeII] and hydrogen were the conspicuous features. The spectrum was very similar to the (recent) spectra of η Carinae.

(e) In 1931 the spectrum had changed further; the salient features were now the forbidden bright lines of [OIII] and [AIV], as well as the bright lines of H, HeI, and HeII; the [FeII] lines had all but disappeared.[109] The two last stages are typical in the development of the spectrum of a nova, such, for example, as Nova Pictoris 1925. An even closer parallel is probably presented by η Carinae, which is, however, developing still more slowly, and has not reached stage (e), if, indeed, it ever does reach it.

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* Possibly Espin's observation of bright Hγ, without other hydrogen lines, may refer to 4363 [OIII].

[104] Ap.J., 25, 281, 1907.

[105] A.N., 208, 363, 1919.

[106] A.J., 32, 37, 1919.

[107] P.A.S.P., 31, 226, 1919.

[108] P.A.S.P., 40, 252, 1928; *see also* Mt. W. Rep., p. 274, 1920-21.

[109] Mt. W. Rep., p. 162, 1931-32; Joy, P.A.S.P., 43, 353, 1931.

There is nothing in the behavior of RT Serpentis to differentiate it from the other novae excepting its relatively slow development. We can scarcely escape from the conclusion that it is undergoing an essentially similar process. The fact that the nova phenomenon can take place very slowly must be kept in mind when theoretical interpretations are attempted. We note, however, that the initial impulse does not seem to have been particularly slow: the initial brightening, to the eleventh magnitude, cannot have occupied more than about forty days. The maximum lasted almost five thousand days; the star is at present much brighter than it was before its outburst, and continued studies of its brightness would be very interesting.*

Nova (η) *Carinae.*—From the light curve[110] during the past century, it is clear that η Carinae developed even more slowly than RT Serpentis, remaining at maximum for upwards of twenty years. It had several subsidiary rises during the main maximum. It is still an eighth magnitude object, and is probably far from the end of the changes that began when it brightened more than a hundred years ago; it should be watched for further changes of brightness and of spectrum.

Unfortunately no spectroscopic observations could be made during or immediately after the maximum. The Harvard spectra[111] show that the star has changed appreciably even during the last fifty years. The first available observation shows a spectrum of Class Feq, primarily an absorption spectrum; but this soon gave place to the striking emission that now characterizes the spectrum. The forbidden lines of ionized iron are particularly prominent,[112] so that a spectrum in which they appear is apt to be described as "resembling η Carinae."

The bright lines are exceedingly narrow, and this is in line with the general observation that the slower the development of a nova, the smaller is the radial velocity of the ejected material. The separation of η Carinae into several hazy components has been suspected by van den Bos.[113]

If the star is connected with the surrounding nebula, as Bok suggests that it may be,[114] its absolute magnitude at maximum was at least —11, far brighter than that known for any other normal nova. It would in that case be the only nova, except Nova Persei 1901, that was connected with nebulosity, but Bok has shown that the brightening of the star was not in this case accompanied by an obvious brightening of the nebula.

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* In one of the early announcements (Adams and Joy, P.A.S.P., 36, 139, 1924) it was stated that the radial velocity varied between +44 km/sec and +125 km/sec, and that "the change shown is of long period and continually decreasing velocity". This condition is not borne out by the published velocities (P.A.S.P., 40, 252, 1928); moreover, in the recent observations, the radial velocity deduced from the known bright lines is +92.3 km/sec, "nearly the same as that found from the absorption lines when the star was at maximum light" (P.A.S.P., 43, 353, 1931). Perhaps the conclusion that should be drawn is that this velocity is the actual velocity of the star; the apparent changes of velocity during maximum brightness may plausibly be connected with the changing intensity of the bright components of the lines from which the velocities are deduced (see the discussion of these changes for Nova Herculis, p. 259).

[110] Innes, Ann. Cape Obs., 11, 75B, 1903; Ludendorff, Handbuch d.Ap., 6, 67, 1928.

[111] Miss Cannon, H.C., 59, 1901; H.A., 28, 175, 1901; 76, 36, 1916; Miss Hoffleit, H.B., 893, 1933.

[112] Merrill, P.A.S.P., 39, 363, 1927; Ap. J., 67, 391, 1928.

[113] M.N., 92, 19, 1931; *see* Stratton, Handbuch d.Ap., 7, 681, 1936.

Nova (P) Cygni 1600.—A detailed light curve for P Cygni cannot be reconstructed from the records; we know, however, that it brightened to the third magnitude in 1600[115] and again in 1657-9, and underwent several subsequent smaller changes. It was, accordingly, not like any of the novae hitherto described, which differed in the speed rather than in the nature of their changes. Probably its light curve was not unlike that of AG Pegasi (p. 267).

The post-maximum spectrum of Nova Cygni 1600 has been extensively studied; a summary of early work is given by Beals.[116] Detailed studies of the current spectrum have been made by Beals[117] and by Struve.[118] Beals describes his general conclusions as follows: "The variation in the emission/absorption ratio [may] be interpreted as due to a stratification of the nebulous envelope surrounding the star, the atoms of highest ionization potential being found nearest the stellar surface while atoms of low ionization potential occup[y] shells of larger diameter farther from the star." The analogy with the structure of a planetary nebula is obvious. Struve[119] reaches essentially the same conclusion: "The elements of high ionization potential are found to originate at greater depths in the shell than the elements of low ionization potential. This suggests that the density of the shell decreases outward slower than $1/R^2$, or that the dilution constant increases more rapidly than R^2. The radial velocities indicate that [the mean velocity] increases with the intensity of the line and decreases as we pass from the elements of low ionization potential to those of high ionization potential. This suggests an accelerated outward motion of the shell . . . The intensity gradient of the HeI lines is steep, suggesting active turbulence."

Both Beals and Struve give excellent summaries of the various measures that have been made of the temperature of P Cygni; it has long been known that the color temperature was too low to be compatible with the spectrum. But the recent theoretical work of Kosirev[120] and Chandrasekhar[121] has shown that a continuously expanding photosphere, such as the observations indicate P Cygni to possess, would give the observed type of energy distribution, deviating greatly from that of a black body.

The variations of the spectrum of P Cygni have been described by Gerasimovič,[122] who considered that for some lines the early Harvard spectra showed a shift of the absorption components from the violet to the red side of the bright lines. The more recent work of Wilson,[123] however, has shown that this conclusion was based on a misinterpretation of the absorption which normally lies on both sides of the bright lines of hydrogen. Although the observations made by Gerasimovič, and those of Wilson, point to a variation in the intensity of these absorption lines, the peculiar type of change described by Gerasimovič cannot be substantiated by a re-examination of the spectra from which he deduced it.

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[114] Harv. Repr. 77, 1932; a long controversy raged on the subject in the sixties and seventies of the last century.

[115] Ludendorff, Handbuch, d.Ap., 6, 69, 1928.

[116] Observatory, 57, 319, 1934.

[117] *Op. cit.*; M.N., 95, 580, 1935.

[118] Ap.J., 81, 66, 1935.

[119] *Op. cit.*

[120] M.N., 94, 430, 1934.

[121] M.N., 94, 444, 1934.

[122] H.B. 852, 1927.

AG Pegasi.—Although not conventionally regarded as a nova, AG Pegasi provides an obvious parallel with P Cygni; and possibly the differences that appear to exist between the two stars are merely reflections of the fact that the interval since the brightening of AG Pegasi is shorter than that since P Cygni became a "nova" in 1600. The light curve[124] is shown in Lundmark's paper to have had a range of 3^m. To describe the spectrum[125] would be out of place here; we shall only mention that it is a complex of dark and bright lines, including the forbidden lines of ionized iron; and that there are rather slow variations of radial velocity, different for different groups of lines.

The present chapter, which opened with a description of the well-known characteristics of normal novae, has ended by including a number of stars (AG Pegasi, RT Serpentis, P Cygni) that are very far from satisfying the usual criteria for a nova. What, then, is a nova?

It is certain that if a nova is defined by the process that is taking place in its atmosphere, the class must be even further widened. The Wolf-Rayet stars are surrounded by atmospheres that are expanding with speeds comparable to those found in the spectra of normal novae—they have been called the "permanent novae."

The analogy may be pushed a little further. There are objects that furnish parallels to novae in all stages of their development. For the pre-maximum stages we may point to α Cygni, which is indeed slightly variable and gives evidence of an expanding atmosphere. The Wolf-Rayet stars furnish a parallel for the immediately post-maximum stages. The planetary nebulae of Type Pd (with [OIII] 4363 the predominant bright line) furnish a parallel for the next, or "auroral," stage; and the majority of the planetary nebulae, with [OIII] 4958, 5007 predominant, represent the "nebular" stage. Even in absolute luminosity these classes of objects are not very far from representative of the novae at the corresponding stages. The suggestion remains that the "nova process" may not only be studied in the rapidly varying objects that attract immediate attention by their outbursts and changes, but also in these slowly developing bodies, that represent all the stages of their evolution.

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[123] Ap.J., 84, 1, 1936.

[124] Lundmark, A.N., 213, 93, 1921; 224, 146, 1925; H.B. 762, 1922.

[125] Merrill, Mt. W. Contr. 381, 1929.

CHAPTER VIII

THE CATACLYSMIC VARIABLES, II

THE SUPERNOVAE

There was a young man who said: "Hush,
"I perceive a young bird in that bush."
When they said: "Is it small?"
He replied: "Not at all;
"It is four times as big as the bush."

Edward Lear

There is good evidence for the existence of a group of novae that are several magnitudes brighter absolutely than the galactic novae commonly observed. These stars have received the somewhat illogical name supernovae*; a list of those that appear to be well attested is given in Table VIII, I. The first compiled list of supernovae, in which attention was called to their great luminosity and common characteristics, was given by Shapley.[1] Lundmark[2] made a similar study a little later.

42. Properties of Supernovae.—The supernovae attain absolute visual magnitudes of about -14 at maximum; this estimate is based on Shapley's value of $-14.5_{pg} = -15.4_{vis}$[3] for the integrated brightness of the average galactic system. The average supernova attains at maximum a photographic magnitude about two magnitudes fainter than the integrated brightness of the galaxy in which it appears. The most recent determination, by Baade,[4] gives a value $m_{nov} - m_{neb} = 2^m.6$. The best known and brightest of the supernovae, S Andromedae, which appeared in 1885 in the Andromeda nebula[5], had at maximum an absolute visual magnitude —14.7 on the basis of a distance modulus 22.2 for the nebula itself. As the nova was probably not as red as the galaxy at maximum (though on this point a wide difference of opinion is legitimate), it was thus not far from typical in luminosity; if it had a zero color index when at its brightest, its absolute photographic magnitude would have been about —14. Its relatively well-observed light curve is probably representative, but there is an indication that the supernovae, like the novae proper, display a certain variety in their light curves.

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*The word supergiant does not furnish an excuse; for "giant" implies size, a quality in which the supergiants surpass the giants, but "nova" (itself an inaccurate term) implies newness, and the supernovae do not excel the novae in this point. The alternative name, "upper class novae", used by Lundmark, scarcely improves matters by introducing an anthropomorphic parallel; and as the word supernova is no more illogical than a number of others that are in current use, and is, moreover, firmly entrenched, we shall use it in what follows.

[1] P. A. S. P., 29, 214, 1917.

[2] Kungl. Svensk. Vetens. Handl., 60, No. 8, 1920.

[3] P. N. A. S., 19, 594, 1933.

TABLE VIII, I

LIST OF SUPERNOVAE

System							
N G C.	Messier	Desc.	Mag.	Date of Appearance	Observed m_{max}	Spectrum	Notes
224	31	Sb	5±	1885 Aug.	6.5	Qu?	1
				1664 ??	6?	..	
1003	..	Sc		1937 Sep.	13.3	Q?	2
2403	..	Sc	10.2	1910 Feb.	16.5	..	3
2535	..	S	12.9	1901 Jan.	13.3	..	4
2608	..	S	12.9	1920	12.0	..	5
2841	..	Sb	10.5	1912 Feb.	16	..	6
3147	..		..	(1914 Apr.)	13.5	..	7
4157	..	Sc	12.	1937	14.6:	..	8
4273	..	Sb	12.2	1936 Jan.	14.4	Qun!	9
4303	61	SBc	10.4	1926 May	12.	Qun!	10
4321	100	Sc	10.8	1901 Mar.	13.5	..	11
				1914 Mar.	14.	..	
4424	..	S:	12.6	1895 Mar.	10.5	..	12
4486	87	E	10.7	1919	11.5	..	13
4527	..	S	11.3	1915 Mar.	14	..	14
5236	83	Sc	8.0:	1923	14	..	15
5253	..	Sa	10.8	1895 Jul.	8.0	Qun!	16
5457	101	Sc	9.0	1910 Feb.	10.8	..	17
6496	..	S		1917 Jul.	14.6	Qun!?	18
IC 4182	..	S		1937 Aug.	8.4	Qun!	19
IC 4719	..	S(dbl)	14.5	1934	13.8	..	20
Galaxy	..	S?	..	1572	—3.5	..	21
				1604	—2.5	..	22
				Before 1572			23

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[4] Quoted by Zwicky, P. A. S. P., 49, 204, 1937.

[5] *See* p. 271.

NOTES TO TABLE VIII, I

1. *SN 1885 NGC 224.*—The well-known star S Andromedae. Light curve compiled from numerous visual observations to which references are made, given by Lundmark (Kungl. Svensk. Vetens. Handl., 60, 55, 1920). Discussion of spectrum, compiled from numerous visual observations (with references), made by C. Payne-Gaposchkin (Ap. J., 83, 245, 1936). The light curve resembled that of an ordinary nova; the spectrum was strong in continuous light, with weak bright bands superimposed, and has been tentatively classed Qu.

SN 1664 NGC 224.—Lundmark (Kungl. Svensk. Vetens. Handl., 60, 60, 1920) suggested the possibility that another sixth magnitude nova appeared in the Andromeda nebula in 1664, basing his suggestion on an observation by Bullialdus that the nebula looked unusually bright in that year. The suggestion must be accepted with reserve, although the appearance of two supernovae in one nebula within two hundred years is not unlikely, having been actually observed in N. G. C. 4321.

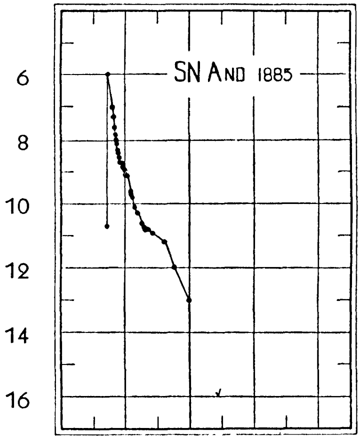

Figure VIII, 1.—Light curve of the supernova S Andromedae, compiled from various sources by Mr. Campbell, with whose kind permission it is reproduced. The observations cover the interval from J.D. 2409700 to J.D. 2410100.

2. *SN 1937 NGC 1003.*—Discovered by Zwicky (*see* H. A. C. 429, 1937), this supernova rose to about the thirteenth magnitude. Light curves have been derived by Miss Hoffleit and Cunningham (unpublished; kindly communicated to authors) and by van Schewick (Die Sterne, 18, 71, 1938). The rise and development seem to have been rather more gradual than for the more rapid of the normal novae. The considerable positive color index, observed as it was a couple of weeks after maximum light, is no more than an indication of the presence of bright bands in the yellow (or red). The spectrum is reported to have been found by Strohmeier (*see* Die Sterne, 18, 71, 1938) to "resemble that of an early B star . . . only HeII 5411 and the broad nebular lines near λ5000 appear in strong

emission, while the neutral helium lines appear in absorption." For a spectrum of a supernova, two weeks after the maximum, this appearance is very surprising, and adds greatly to our scanty knowledge.

3. *SN 1910 NGC 2403.*—Ritchey (P. A. S. P., 29, 211, 1917) observed a star of magnitude 16.5, invisible on other plates, even to an exposure of 7 hours. This observation makes the star six magnitudes fainter than the integrated brightness of N. G. C. 2403, but if allowance is made for the possibility that the maximum was missed, the object is probably a supernova. The range of more than four magnitudes puts it outside of the Cepheid class; and it is about six magnitudes too bright to be a normal nova, if at the distance of the nebula on which its image is projected. On the other hand, if it is a normal galactic nova it is at an improbably large distance.

4. *SN 1901 NGC 2535.*—This nova was discovered by Reinmuth (A. N., 221, 47, 1923); its magnitude was 15 on January 10.4, and 13.3 on January 18.4; in other words, it took more than a week to increase in brightness less than three magnitudes. Note that the system in which this nova occurred is erroneously given as N. G. C. 2355 (a faint galactic cluster) in the Handbuch der Astrophysik (6, 256, 1928), and that the error is copied by Vorontsov-Velyaminov (New Stars and Galactic Nebulae, 1935).

5. *SN 1920 NGC 2608.—See* Lundmark, P. A. S. P., 35, 116, 1923.

6. *SN 1912 NGC 2841.—See* Pease, P. A. S. P., 29, 213, 1917.

7. *SN 1914 NGC 3147.*—Discovered by Mrs. Isaac Roberts (P. A. S. P., 29, 214, 1917; C. R., 173, 1072, 1921). Compare, however, Lundmark (P. A. S. P., 34, 53, 1922).

8. *SN 1937 NGC 4157.*—The observed magnitude of the nova was 16.2; that given in the table is Zwicky's estimate of the maximal magnitude (P. A. S. P., 49, 204, 1937). N. G. C. 4157 is a spiral seen on edge, and Zwicky states that the nova lies in a dark lane.

9. *SN 1936 NGC 4273.*—The nova was discovered by Hubble and G. Moore (P. A. S. P., 48, 110, 1936); the light curve is given by Baade (P. A. S. P., 48, 227, 1936); the spectrum is described by Humason (P. A. S. P., 48, 110, 1936) with a figure. The spectrum, a hundred days after maximum, is thus described by Baade (P. A. S. P., 48, 228, 1936): "The . . . spectrum is unique: in the photographic region between 5000 and 3900 A it consists of a single wide band of great intensity which coincides approximately with the f-g band in Humason's reproduction of the spectrum. Measures of the bright bands by Mr. Humason led to the following results:

	Measured λ	Corrected λ
Violet edge of band	4572.4	4538.9
Red edge of band	4777.5	4742.4

The last column gives the wave lengths corrected for the measured red shift (= + 2200 km/sec) of N. G. C. 4273.

"The resulting wave length for the center of the band, 4640.7A, suggests that it is due to the well-known NIII line which is a prominent feature in the spectra of common novae during their later stages . . . The new spectrum leaves no doubt that the interpretation of the earlier spectra as a superposition of very wide emission lines is correct".

10. *SN 1926 NGC 4303.*—The nova was discovered by Wolf and Reinmuth (H. B. 836, 1926). Spectrum, taken in 1926 by Nicholson, published in a paper by Humason (P. A. S. P., 48, 110, 1936): "remarkably similar" to the earlier spectrum of the nova in N. G. C. 4273, described above.

11. *SN 1901 and SN 1914 NGC 4321.*—Both were discovered by Curtis (L. O. B. 300, 1917).

12. *SN 1895 NGC 4424.*—VW Virginis, discovered by Wolf (A. N., 226, 76, 1925).

13. *SN 1919 NGC 4486.*—*See* Lundmark, M. N., **85**, 888, 1925.

14. *SN 1915 NGC 4527.*—Discovery, Curtis, L. O. B. 300, 1917.

15. *SN 1923 NGC 5236.*—Discovery, Lampland (*see* H. B. 786 and 787, 1923); it is considerably fainter, relative to Messier 83, than are the other stars mentioned in the table, relative to the systems in which they appeared.

16. *SN 1895 NGC 5253.*—This is Z Centauri, discovered by Mrs. Fleming (*see* Pickering, H. C. 4, 1897). For a discussion of the spectra of star and nebula, *see* C. Payne-Gaposchkin, Ap. J., **83**, 173, 1936. The spectrum consisted of wide, bright bands, notably one centered near 4640. The system N. G. C. 5253, though first thought not to be a typical spiral, is given in the recent Harvard catalogue as Sa.

17. *SN 1910 NGC 5457.*—The star SS Ursae Majoris, discovered and observed by Wolf, A. N., **180**, 375, 1909; **181**, 179, 1909; **184**, 159, 1910; Pop. Astr., **17**, 326, 580, 1910). Three other novae discovered in the same system seem now to have been normal novae (*See* Table VII, II). *See* Ritchey (P. A. S. P., **29**, 211, 1917); his faint "novae" now seem to have been Cepheid variables (Hubble and Humason, Mt. W. Contr. 427, 1931).

18. *SN 1917 NGC 6496.*—This nova was discovered by Ritchey (P. A. S. P., **29**, 211, 1917). Spectrum, a month after maximum, obtained by Ritchey and Pease: "continuous spectrum is strong, and crossed by what appears to be a series of bright bands".

19. *SN 1937 IC 4182.*—Although the system in which it appeared is faint, this object, discovered by Zwicky, is the third brightest supernova ever found (*See* Harvard Announcement Card 427, 1937). The light curve is given by van Schewick (Die Sterne, **18**, 70, 1938). The decline in brightness appears to be steady and not remarkably rapid. The spectrum is probably the most completely studied of all supernova spectra, having been photographed, among other places, at the Lick Observatory by Popper (P. A. S. P., **49**, 283, 1937), at Potsdam by Strohmeier (Zs. f. Ap., **14**, 227, 1937) and also by Walter, and at Mount Wilson. All observers agree that the spectrum is characterized by wide bright lines on a rather strong continuous background, and the features of the spectrum are similarly described by all. The identifications are not, however, treated with the same unanimity. The matter is further discussed in the text.

20. *SN 1934 IC 4719.*—Discovered by Miss Boyd (H. B. 907, 1937).

21. *B Cassiopeiae.*—This star, discovered in 1572 by Tycho Brahe, has been placed among the supernovae because of its great brightness and the fact that its range seems to have been 19 magnitudes, if the star at present identified by Lundmark and Humason (M. N., **85**, 885, 1925) as the nova is the right one.

22. *Kepler's Nova.*—Lundmark (*see*, for example, Lund Medd., Series 2, No. 74, 1935) considers this star a supernova.

23. *The pre-Tychonic Novae.*—Lundmark (Lund Medd., Series 2, No. 74, 1935) gives —14 as the average absolute magnitude at maximum of these stars; but the individual identifications are very conjectural, and it is unlikely that there have been more than *one* or *two* galactic supernovae within historic times.

In Table VIII, I it is evident that there is a considerable dispersion in the difference of brightness between nova at maximum and integrated nebula. We cannot draw the conclusion that the dispersion in absolute magnitude at maximum is large for supernovae, for the dispersion in absolute magnitude for galaxies is itself considerable. For example, the nebula N.G.C. 1003, the site of one of the brightest of the supernovae, is itself a faint galaxy; Humason, however, points out that it is a "dwarf" nebula, of low surface brightness, giving a velocity of but +475 km/sec, and accordingly nearer to us than would be inferred from its brightness alone[6]. More data than are now at our disposal are needed, before the dispersion in absolute magnitude at maximum can be evaluated for supernovae.

The problem of the nature of the supernovae, and of their relationship to other novae, is one of the most fascinating in variable-star astronomy. At present it is hampered both by lack of data and by difficulties in interpreting the data that we have. The greatest puzzle is presented by the spectra. We possess photographic records of the spectra of six supernovae, and visual observations of a seventh. It is only a few years since the spectra of supernovae were vaguely thought to possess a (dark) banded structure, unlike those of any other stars. The so-called dark bands have not, however, the well defined "heads" shown by the absorption bands of molecular spectra; and the idea that the spectra actually consist of wide *bright* bands occurred simultaneously to several astronomers.[7] The bands are far wider than those found in the spectra of any other objects (save, possibly, some of the Wolf-Rayet stars); it is not difficult to suppose that the width is associated with very large velocities of ejection, so that the whole phenomenon is on a scale worthy of the great luminosity of these stars.

The identification of the features of the spectrum of a supernova presents real difficulties, and it is little wonder that the descriptions of the visual observations of the spectrum of S Andromedae seemed indefinite and conflicting. With velocities of the order of 5000 km/sec, there is so much overlapping of the spectral lines, widened by the Doppler effect, that the whole aspect of the spectrum is altered, and identification from

[6] P. A. S. P., 50, 55, 1938.

[7] Vorontsov-Velyaminov, Rus. Astr. Jour., 8, 42, 27, 1931; A. N., 242, 208, 1931; "New Stars and Galactic Nebulae", 221, 261, 1935; C. Payne-Gaposchkin, Ap. J., 83, 173 and 245, 1936; *see also* note No. 18, Table VIII, I.

inspection, either of spectra or microphotometer tracings, is virtually impossible. Let it be assumed, for instance, that a spectrum contains two equally strong bright lines, separated by an undisturbed interval of continuous spectrum fifty Angstroms wide. Now let the material causing the bright lines be given an outward velocity; the bright lines will widen, with square contours, by an amount governed by the velocity. Their inner edges will approach, the strip of undisturbed continuous spectrum becoming narrower. At the point where their inner edges overlap, their contours (which are additive) will combine, giving a narrow bright line of twice the intensity of either, and of apparent wave-length half-way between their wave-lengths. Phenomena of this sort were already a source of trouble in identifying the lines in the spectrum of the normal nova, Nova Aquilae 1918; and the extent to which they can modify the appearance of the spectrum of a supernova can only be appreciated by building up such a spectrum graphically. With very large velocities (5000 km/sec) and numerous lines, it is possible to obtain the effect of maxima only *between* the centers of the actual lines present; the normal positions of the lines themselves being occupied by the widened lines, where they overlap least with their neighbors, and looking like continuous background free from lines altogether. It is possible, by taking the normal intensities of lines of H, HeI, HeII, and NIII with the intensities appropriate to the "4640 stage" of an ordinary nova (such as Nova Aquilae 1918), to predict the distribution of the bright lines for a series of high velocities of ejection; and the general form of the featureless contours of the supernova spectrum in the photographic region can readily be reproduced by the right choice of velocity.

There remains the alternative that the spectra of the supernovae consist of light arising from matter under conditions otherwise unobserved. This is an interesting idea; but it can only be substantiated by the total failure of more orthodox ways of interpreting the spectra. The interpretation suggested in the last paragraph appears to the authors to offer a more satisfactory basis for understanding the spectra of the supernovae. The Potsdam workers seem to consider that the spectra show features similar to those of the novae proper. Merrill expresses the same thought: "the spectra, although observed as yet only on a small scale, appear to have the same general characteristics" as those of ordinary novae.[8] We have described them in the conventional notation as of spectral class Qun!

We are concerned in the present chapter with the recording and grouping of observations, not in their interpretation nor in the discussion of theories as to the nature of the supernova process. Insofar as they require that the outburst of a supernova (but not that of an ordinary nova) be accompanied by the observation of increased intensity of cosmic radiation, it may be said that the evidence on this point is at present negative. The astronomical importance of cosmic rays should never be forgotten; but it would seem that the problem could best be approached from another side.

For an ordinary nova, a spectrum of Class Qu is associated with a temperature not greater than 30,000°; if the nebular lines N_1 and N_2 of [OIII] are present, they are at least inconspicuous. The temperature of a nova in the nebular stage (Qy, Qz) is[9] about 50,000°, which must therefore be considered an upper limit for the four supernovae mentioned, at the dates on which their spectra were secured, because they had not yet reached Class Qy or Qz. The available evidence concerning the spectra of novae indicates that their maximal temperatures are probably even lower[10].

The spectra of supernovae do not lend themselves to quantitative work, but some qualitative conclusions can be drawn from them. Their bright bands are about as strong (relative to their total brightness) as in the spectra of normal novae at a similar stage; thus it is possible that about the same fraction of the star is involved in the outburst. The loss of mass, by radiation and ejection, is therefore probably in about the same ratio to the total mass for novae of both sorts. The radial velocities shown by the supernovae are about a thirtieth of the velocity of light. Although we shall not here enter into a

[8] The Nature of Variable Stars, 96, 1938.

[9] Vorontsov-Velyaminov, Zs. f. Ap., 10, 365, 1935.

[10] Menzel and Payne, P. N. A. S., 19, No. 7, 1933; *see* Whipple and C. Payne-Gaposchkin, H. C. 412, 1936, for the increase in temperature of one nova (Nova Herculis 1934) immediately after maximum.

consideration of the problem of how their surfaces can be set in motion with such speeds, we may mention that at such velocities it is possible to obtain spectroscopic Doppler effects that will cause considerable differences of detail between the spectra of the atmospheres of supernovae and those of less violent novae of similar atomic composition.

The cosmic status of the supernovae is still in doubt. The writers are of the opinion that a supernova differs only in brightness and radial velocity from a nova—that is, the phenomena differ in scale rather than in kind. Possibly we may regard them as novae that have developed from giant, rather than from dwarf, stars. The frequency of supernovae (perhaps one ten-thousandth of that of novae) may well represent the relative commonness of the giant and dwarf stars from which they originate.

In the previous chapter an attempt was made to derive distances of normal novae on the basis of a formula connecting radial velocity, speed of rise, and surface brightness. If, assuming the third quantity to be the same, we insert the adopted high velocities for supernovae, and make use of the few known light curves to determine a rate of brightening, we obtain absolute magnitudes and distances for the supernovae, of the same order as those given earlier in the present chapter. This very tentative result confirms our impression that the novae differ from the supernovae chiefly in scale[11].

On the discovery of a galactic nova, speculations are often made as to whether the star can be a supernova. It is suggested that a supernova should be at once recognizable by the extreme width of its bright bands, the light curve and spectrum otherwise resembling those of ordinary novae. Further, a galactic supernova would almost certainly appear brighter than zero apparent magnitude, because the galactic system is comparatively small.

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[11] *See* C. Payne-Gaposchkin, P. N. A. S., 22, 332, 1936; a complete bibliography of supernovae has been compiled by Helen B. Sawyer (J.R.A.S.C., 32, 86, 1938).

CHAPTER IX

THE CATACLYSMIC VARIABLES, III

THE SS CYGNI STARS

> . . . . Headlong extinct to one dark center fall,
> And death, and night, and chaos mingle all;
> Till o'er the wreck, emerging from the storm
> Immortal nature lifts her changeful form,
> Mounts from her funeral pyre on wings of flame,
> And soars and shines, another and the same.
>
> Erasmus Darwin

The stars that have received their name from the well-known variable SS Cygni* form one of the best defined of the groups with which we have to deal. They remain at minimum, with comparatively steady light, for intervals ranging from about twenty to about a hundred and fifty days. At roughly periodic intervals they increase in brightness, usually with great suddenness, and, after a brief maximum of variable duration, they decline, usually more slowly than they rose, to their original brightness. The form of the light curve is very typical, and there can be no doubt whether a well-observed star is a member of the class or not.

A second group of stars, differing in length of cycle and in other characteristic ways during certain maxima, is closely associated with the SS Cygni stars; it takes its name from the type star, Z Camelopardalis, but there is every reason to consider that the process represented is essentially similar to that undergone by the SS Cygni stars, and in the present chapter they are considered as forming a single group. Many of the SS Cygni stars are very faint, and our knowledge of their spectra and colors is scanty; therefore such matters have not hitherto entered the criteria adopted for membership in the class.

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* Sometimes they are called after the other well-known variable U Geminorum; we have preferred to call them after the better-known star.

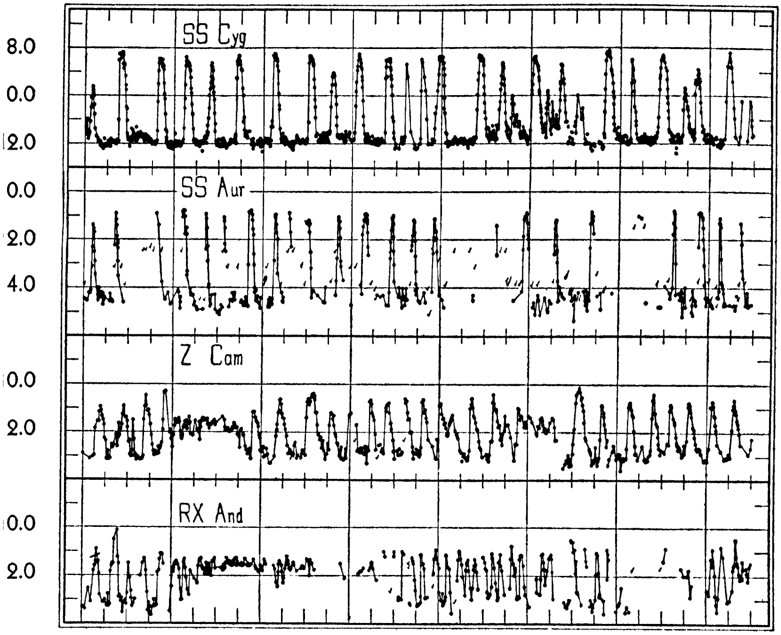

Figure IX, 1.—Light curves of "SS Cygni" variables:

SS Cygni	between J.D.	2427500 and 2429050
SS Aurigae		2427500 and 2429050
Z Camelopardalis		2426900 and 2427750
RX Andromedae		2426900 and 2427750

All the light curves have been compiled by Mr. Campbell from the visual observations made by the A.A.V.S.O. and other groups of observers, and it is with his permission that they are reproduced here.

43. **Members of the SS Cygni Class.**—Table IX, I contains a list of all stars that have been assigned during the last decade to the class now considered. Critical notes concerning the observations are given in the column headed "Remarks", and references follow the table.

A comparison with the corresponding table for the stars that have been assigned to the R Coronae Borealis class (Table X, I) will show that there have been comparatively few erroneous ascriptions to the SS Cygni class. This is a result of the simple

TABLE IX, I

VARIABLES ASSIGNED TO THE SS CYGNI CLASS

Star	Remarks	Reference
RX And	See Table IX, VI*; Z Cam group	Jacchia, Bologna Publ., 2, 8, 1932; Campbell, H. C. 382, 1933.
VZ Aqr	Doubtful; possible long or intermediate period; *11.8–[16.0*	Parenago, N. N. V. S., 4, 228, 1933.
CV Aqr	See Table IX, VI; SS Cyg group	Olmsted, H. A., 90, 170, 1934.
UU Aql	See Table IX, VI; SS Cyg group	O'Connell, H. B. 890, 1933.
FO Aql	Perhaps a member; little known; *13.0–[16.0*	Hoffmeister, A. N., 238, 191, 1930.
KX Aql	See Table IX, VI	Hoffleit, H. B. 887, 1932.
AT Ara	See Table IX, VI	Boyd, H. A., 90, 182, 1934.
BF Ara	See Table IX, VI	Boyd, H. A., 90, 182, 1934.
SS Aur	See Table IX, VI; SS Cyg group	*See* G. u. L., II, 1, 104, 1934.
RV Cnc	Doubtful; 9.7–12; F8	Jacchia, *see* G. u. L., II, 1, 149, 1934.
Z Cam	See Table IX, VI; Z Cam group	
EP Car	See Table IX, VI	Hertzsprung, B. A. N., 4, 172, 1928.
MU Cen	See Table IX, VI	Rybka, Acta Astr., 2, 92, 1934.
NN Cen	See Table IX, VI	Wright, H. A., 90, 178, 1934.
BP CrA	Doubtful; *13.9–15.6*	van Gent, B. A. N., 7, 21, 1933.
SS Cyg	See Table IX, VI; SS Cyg group	Campbell, H. A., 90, No. 3, 1934.
FO Cyg	Doubtful; long period?; *14.5–[16.0*	Hoffmeister, A. N., 234, 35, 1928; *ibid.*, 240, 249, 1930.
HN Cyg	Doubtful; *13.5–15.5*	Hoffmeister, A. N., 236, 240, 1929; *ibid.*, 244, 105, 1931.
V337 Cyg	Doubtful; long period; *14.4–[16.5*	Baade, A. N., 232, 69, 1928.
XZ Eri	See Table IX, VI	Hughes, H. A., 90, 170, 1934.
AH Eri	See Table IX, VI	Hughes, H. A., 90, 170, 1934.
AQ Eri	See Table IX, VI	Hoppe, A. N., 254, 369, 1935.
U Gem	See Table IX, VI; SS Cyg group	*See* Prager, G. u. L., II, 2, 100, 1936.
AU Gem	Possibly a member; *12.3–[15.1*	Kukarkin, N. N. V. S., 3, 135, 1931.
AW Gem	See Table IX, VI	*See* A. N., 249, 263, 1933.
CH Her	See Table IX, VI	Hoffmeister, A. N., 236, 239, 1929.
X Leo	See Table IX, VI	Jacchia, Bologna Publ., 2, 9, 1931.
TU Leo	Doubtful; eclipsing?; *11.7–14.9*	Parenago, N. N. V. S., 4, 279, 1934.
BR Lup	See Table IX, VI	Swope and Caldwell, H. B. 879, 1930.
AY Lyr	Probably a member, see Table IX, VI	Zverev, N. N. V. S., 4, 356, 1934.
CY Lyr	See Table IX, VI	Zverev, N. N. V. S., 4, 356, 1934.
AB Nor	See Table IX, VI; probably a member	Caldwell, H. B. 879, 1930.

Table IX, I—*Continued*

Star	Remarks	Reference
HP Nor	Possible member; *12.9–15.3*	Kruytbosch, B. A. N., 7, 255, 1935.
AO Oph	Doubtful; R Coronae Borealis type?; *13.6–17.0*	Parenago, N. N. V. S., 3, 113, 1931.
BI Ori	See Table IX, VI; member?; Z Cam group	Ludendorff, Handb.d.Ap., 7, 625, 1936.
CN Ori	See Table IX, VI; member?; Z Cam group	Ludendorff, Handb.d.Ap., 7, 625, 1936.
CZ Ori	See Table IX, VI; member?	Hoffmeister, A. N., 233, 34, 1928.
RU Peg	See Table IX, VI; SS Cyg group	Ludendorff, Handb.d.Ap., 7, 625, 1936.
TZ Per	See Table IX, VI; Z Cam group	Ludendorff, Handb.d.Ap., 7, 625, 1936.
UV Per	See Table IX, VI; SS Cyg group	Ludendorff, Handb.d.Ap., 7, 625, 1936.
CL Sco	See Table IX, VI	Luyten, H. B. 852, 1927.
MM Sco	See Table IX, VI	Boyd, H. A., 90, 177, 1934.
UZ Ser	See Table IX, VI	N. N. V. S., 3, 112.
VW Tuc	See Table IX, VI	Hughes, H. A., 90, 171, 1934.
SU UMa	See Table IX, VI	Jacchia, Bologna Publ., 2, 9, 1931.
TW Vir	See Table IX, VI; SS Cyg group	O'Connell, H. B. 890, 1933.
UY Vul	Doubtful; *14.1–[16.0*	Wolf, A. N., 221, 269, 1923; Koyama, Kyoto Bul. 256, 1933.

* Throughout this table, IX, VI should read IX, II.

and specific criteria, which result from the distinctiveness of the SS Cygni type of variability. It will also be noted that if the stars in Table IX, I, that do not appear in Table IX, II, are, after all, members of the SS Cygni group, the conclusions drawn later about apparent magnitude and galactic position will be comparatively unaltered.

The stars that can definitely be assigned to the SS Cygni class are collected in Table IX, II. The letters SS and Z indicate whether the star resembles SS Cygni or Z Camelopardalis.

44. General Properties of the SS Cygni Stars.—The thirty-six stars contained in the table give the following mean values for magnitude, period, and position:

Type	Maximum Magnitude	Range	Minimum Magnitude	Mean Cycle	Galactic Latitude	Mean Spectrum
	m	*m*	*m*	*d*		
SS Cyg	11.0(12)	4.0(8)	(15.0)	62(10)	25°(12)	Bn:
Z Cam	11.0(4)	3.5(4)	14.5	20(4)	22 (4)	F5:
All	11.7(36)	3.7(18)	14.7(18)	51(16)	19 (36)	..
	11.0(18)		(15.4)			

TABLE IX, II

VARIABLES OF THE SS CYGNI CLASS

Star	Designation	l	b	Max.	Amp.	Spec.	Type	Mean Cycle	Ref.
				m	*m*			*d*	
RX And	005840	92°	−22°	10.3	3.6	..	Z	14	
CV Aqr	211*614*	6	−41	*12.4*	]*4.2*	..	SS	..	
UU Aql	195*209*	2	−20	11.0	5.8	..	SS	30–>80	1
KX Aql	192914	19	− 3	13.1	]3.2	..		..	
AT Ara	172*346*	312	− 8	*13.0*	*2.8*	..			
BF Ara	173*147*	312	−10	*13.8*	]*2.2*	..			
SS Aur	060547	134	+15	10.5	4.2	B:	SS	25–103	
Z Cam	081473	109	+34	9.6	3.7	G?	Z	23	
EP Car	102*458*	253	0	*13*	]*3*	..	..	..	2
MU Cen	120*743*	263	+18	*12.4*	*2.6*	..	..	..	
NN Cen	130*760*	273	+ 2	*13.2*	]*3.3*	..			
SS Cyg	213843	57	− 6	8.1	3.9	Bn:	SS	50.3	3
FO Cyg	192730	32	+ 5	*14.5*	]*1.5*	..	..	..	
XZ Eri	040*615*	175	−42	*14.6*	]*1.9*	..	..	..	
AH Eri	041*813*	180	−40	*13.5*	]*3.0*	..	..	..	
AQ Eri	050*104*	170	−24	*12.5*	*4.0*	..	..	..	
U Gem	074922	167	+25	8.8	5.0	On:Cont.	SS	62–257	4
AW Gem	071628	158	+20	*13*	]*4.0*	..	..	..	
CH Her	183024	20	+12	*13.5*	]*2.0*	..	..	..	
X Leo	094512	192	+47	12.0	3.1	..	SS	19	
BR Lup	152*940*	301	+12	*13.5*	]*2.5*	..	..	24:	
AY Lyr	184037	33	+16	12.5	]2.0	..	SS	21:	
CY Lyr	184926	25	+10	12	4	..	..	..	
AB Nor	154*342*	301	+09	*13.9*	]2.*1*	..	..	..	
BI Ori	051800	170	−18	13.2	]2.8	..	Z	19–26	
CN Ori	054*705*	177	−15	11.0	3.7	..	Z	19.2	
CZ Ori	061115	163	+ 1	11.8	4.4	..	..	..	
RU Peg	220912	43	−36	9.0	4.1	..	SS	38–97	
TZ Per	020657	102	− 3	12.4	2.9	f:	Z	21	5
UV Per	020356	101	− 4	*12.4*	]3.6	..	SS	142–400	
CL Sco	164*930*	320	+ 8	*11.1*	*2.4*	..	..	..	
MM Sco	172*442*	315	− 6	*13.0*	]*3.5*	..	..	..	
UZ Ser	180*514*	344	+ 1	*12.6*	*4.0*	..	SS	..	
VW Tuc	001*674*	273	−46	*15.0*	]*1.5*	..	..	..	
SU UMa	080362	122	+33	11.1	2.2	..	SS	18–22	
TW Vir	114*003*	243	+56	*11.8*	]*4.0*	..	SS	23:	

1. Increase 4^m in 24 hours; color index small (O'Connell, H.B. 890, 1933).
2. Increase 1^m in 6 hours (Hertzsprung, B.A.N., 4, 146, 1928).
3. Color index +0.1 (flat maxima); −0.1 (sharp maxima); +0.3 (minimum); apparently consistent with spectrum (Gerasimovič and Payne, H.B. 889, 1932).
4. Color index $+0^m.3$ (maximum), and $0^m.6$ (minimum) (Gerasimovič and Payne, H.B. 889, 1932); color white or bluish white at maximum.
5. Color white (Ludendorff, Handbuch der Astrophysik, 6, 85, 1928).

It appears that the SS Cygni stars differ from the Z Camelopardalis stars principally in period, and somewhat also in mean range. In forming the means, visual and photographic magnitudes have been combined indiscriminately, since the stars seem to be of small color index. If, however, allowance is made for the slender evidence that the Z Camelopardalis stars may be of rather later spectral class than the SS Cygni stars, their average photographic magnitudes at minimum will be brought nearer to those of the SS Cygni stars, and may even be a little fainter. From so small a number of stars it can only be stated that the average apparent magnitude at minimum (regarded, because of the shape of the light curve, as normal brightness) is about 15.0— fainter than the average normal brightness of any other class of variable stars excepting the novae. The qualitative inference to be drawn from this result is that the SS Cygni and Z Camelopardalis stars are absolutely faint. The average galactic latitude is higher than for other types of variable stars (including novae), but is still low enough to indicate an appreciable galactic concentration.

The conclusion that the SS Cygni stars are actually dwarfs was reached by Parenago and Kukarkin[1] on the basis of a discussion of the proper motions of SS Cygni and U Geminorum. They obtain for SS Cygni a total proper motion of $0''.118 \pm 0''.007$, and for U Geminorum, a total proper motion of $0''.058 \pm 0''.004$. An unpublished determination of the proper motion of U Geminorum from Yerkes plates, kindly communicated by Mr. Ebbighausen, confirms the value given by Parenago and Kukarkin. Compare, however, the recent negative parallax published by van Maanen,[1a] together with a redetermination of the high proper motion. The resulting absolute visual magnitude at minimum of $+10^m \pm 3^m$, though probably not more accurate than the published mean error indicates, renders the dwarf nature of the group almost certain.

The color indices of SS Cygni and U Geminorum were found by Gerasimovič and Payne[2] to be somewhat greater at minimum than at maximum, a result confirmed on more general

[1] N. N. V. S., 4, 249, 1934.
[1a] Ap. J., 87, 424, 1938.
[2] H. B. 889, 1932; see Table IX, II, notes.

grounds by Kukarkin and Parenago,[3] who found that the photographic ranges exceed the visual ranges. The colors at minimum suggest spectra of Classes A to F, so that the absolute magnitude quoted above is fainter than would be expected if the stars belong to the main sequence.

There is a definite increase in amplitude, not only from the Z Camelopardalis group to the SS Cygni group, but from the SS Cygni stars of short to long period, and probably for any one SS Cygni star as a function of the length of the preceding cycle. Kukarkin and Parenago[4] have established and discussed this phenomenon, which they regard as forming a link between the SS Cygni stars and the novae[5]. We note that AC Andromedae, the star of the shortest period on their list, is now assigned to the cluster type*.

Only two well-observed novae can be regarded as definitely cyclic: Nova Ophiuchi (RS) 1919 and T Pyxidis; a third possible example is Nova Orionis 1667[6]. The first two objects are well represented by the relation given by Kukarkin and Parenago:

$$\bar{A} = 0.63 + 1.667 \log \bar{P}$$

where A and P represent amplitude and period, the former in magnitudes, the latter in days. A reckless extrapolation of the formula would give for normal novae and supernovae average periods of the order of 10^3 and 10^7 years, respectively, and these values seem not quite unreasonable in the light of the observed frequency of the two types of object. We must not therefore be unprepared to consider the possibility that the novae are cyclic, and related to the SS Cygni stars[7].

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[3] N. N. V. S., 4, 252, 1934.

[4] N. N. V. S., 4, 251, 1934.

[5] See p. 237.

* Regarded at first as a cluster type star by Guthnick and Prager (A. N., 229, 455, 1927), but soon seen to have a light curve variable in speed of rise and fall, in height, form, duration of maxima and in minimum brightness, and not strictly periodic. Lause (A. N., 245, 329, 1932) reached a similar conclusion on the basis of further observations; all three considered that a very short period SS Cygni light curve might fit the case. Lange (Lenin. Bul. 3, 1933) considered the light variation to be of a peculiar and individual kind, and suggested the existence of two simultaneous periods, a suggestion substantiated by Florja (R. A. J., 14, 1, 1937), who has shown that the light curve may be compounded from those of two cluster type stars of equal brightness, but differing in period.

[6] See p. 236.

The most completely observed SS Cygni variable is the type star itself, for which the observations, made continuously by the A.A.V.S.O. over a long interval, have been compiled by Campbell.[8] He has also studied the variety of possible types of maximum (which are representative for the SS Cygni stars as a group). The differences involve height, steepness, and duration of maximum light. As Kukarkin and Parenago[9] pointed out, parallels to the various types of maxima of SS Cygni stars can be found in the types of light curve displayed by novae. In spite of the variety of maxima, and the large deviations from strict periodicity, the conception of a period is still valid for SS Cygni stars. Sterne and Campbell[10] have shown that for SS Cygni itself the frequency distribution of the cycles follows the normal law of errors, the mean cycle being $50^d.3$. Presumably like results would be found if the remaining SS Cygni stars were as fully observed and as rigorously analyzed; and (perhaps with less certainty) the same may be anticipated for the Z Camelopardalis stars. The general results obtained by Sterne and Campbell for SS Cygni, and mentioned in connection with the properties of that star, are probably equally valid for the stars of the group as a whole.

45. General Properties of Z Camelopardalis Stars.—The characteristic by which the Z Camelopardalis type is primarily defined is the occasional halting of the light curve during the fall in brightness, the star persisting at an intermediate magnitude for a considerable interval—sometimes as great as two hundred days[11]. Obviously this feature can be established only by continuous observation, and it is for this reason that a number of faint stars in Table IX, II are not assigned either to the SS Cygni or the Z Camelopardalis class. It appears from the discussion of Table IX, II that the Z Camelopardalis stars have shorter cycles and rather smaller amplitudes, and it is possible that they are of rather later spectral class, than the SS Cygni stars. Possibly, however, on more extensive observation, such stars as SU Ursae Majoris and X Leonis, which have short cycles and small amplitudes, will be found to belong to the Z Camelopardalis group; otherwise we must conclude that there is a real difference between the two groups, despite the close similarity of apparent magnitude, and (probably) of absolute magnitude. But even the characteristic halt on the down branch of the Z Camelopardalis stars finds a parallel in the light curves of such novae as Nova Aurigae 1892, and Nova Herculis 1934; the SS Cygni and Z Camelopardalis stars form together a group as real as the novae.

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[7] See p. 237.
[8] Campbell, H. A., 90, No. 3, 1930.
[9] N. N. V. S., 4, 253, 1934.
[10] H. A. 90, No. 6, 1934.
[11] Jacchia, Bologna Publ., 2, 5, 189, 1933.

We note that there is no obvious difference in luminosity between the SS Cygni and Z Camelopardalis stars, nor do they fall anywhere near the period-luminosity curve for the Great Sequence. If they show any period-spectrum relation, it is in the sense that long period goes with early spectrum—opposite to the relation shown by the Cepheids (the giant members of the Great Sequence), and parallel to the relation for the dwarf members of the Great Sequence and for the (eclipsing) dwarfs, the W Ursae Majoris stars.

46. Properties of Individual Stars.—Only for the three well-observed stars, SS Cygni, U Geminorum, and SS Aurigae, do we possess detailed information. The spectral data, which are of the first importance in interpretation, are unfortunately very limited.

SS Cygni.—The very extensive observations that are available for SS Cygni furnish a basis for describing its type of variation in great detail. Figure IX, 1, illustrates the possible forms of individual maxima, which are represented also by other stars of the group. For instance, SS Aurigae[12] went through a series of "disturbed" maxima in 1928. The observations of the light curve of SS Cygni have been formally analyzed by Sterne and Campbell[13], who deduced a number of associations and correlations between steepness, height, and width of maximum, and length of cycle. One result of their work is that the alternation of wide and narrow minima is a general tendency, not an invariable rule; a breach of this rule had been noted for U Geminorum, for example, by de Roy[14].

[12] Jacchia, Bologna Publ., 2, 5, 189, 1933.
[13] H. A., 90, No. 6, 205, 1934.
[14] J. B. A. A., 41, 282, 1931; *ibid.*, 43, 169, 1933.

The most important published data relating to the spectrum of SS Cygni are contained in the brief note given by Adams and Joy[15]:

"Maximum: Spectrum is continuous with faint dark bands of hydrogen and helium 20 Angstroms wide. Minimum: Strong bright bands of hydrogen and helium about 20 Angstroms wide but not displaced. Possibly a few faint absorption lines. The spectrum of this star bears resemblance to that of novae" (presumably only in the occurrence of undisplaced bright lines at minimum, for there is no record of forbidden lines, which a careful inspection of the available Harvard plates has also failed to show). Neither spectroscopically nor optically is there any sign of surrounding nebulosity. It is very difficult to assign a spectral class, but on the basis of Adams and Joy's description, we have inserted Bn: in Table IX, II.

U Geminorum.—Characterized by a greater range and a longer cycle, U Geminorum is less completely observed than SS Cygni. The data concerning the spectra are somewhat conflicting, but the remark in the Henry Draper Catalogue, that the spectrum appears continuous on the best plates, is probably to be considered the most reliable. Such a description possibly indicates a spectrum of class On or Bn. The color has been described as white or bluish white[16].

SS Aurigae.—The remaining star whose spectrum has been observed, SS Aurigae, shows at maximum wide dark lines ("bands") due to hydrogen and helium[17]; it is white in color. In Table IX, II, the spectrum is tentatively described as Bn:.

[15] Pop. Astr., 30, 103, 1922.
[16] Ludendorff, Handbuch der Astrophysik, 6, 85, 1928.
[17] Annual Report, Mt. W. Obs., 234, 1922.

CHAPTER X

THE CATACLYSMIC VARIABLES, IV
THE R CORONAE BOREALIS STARS

> Plus ça change, plus c'est la même chose.
>
> Voltaire

The cataclysmic variables hitherto described are essentially dwarf stars. The R Coronae Borealis stars, on the other hand, are supergiants. They are the only intrinsic variables that undergo sudden *drops* in brightness. Thus they differ in their most conspicuous properties from the other stars in whose company we have placed them.

47. Definition and Critical Selection.—The star after which the class is named, R Coronae Borealis, is a typical representative of it in light variations and in spectrum; it is furthermore the best observed member. The R Coronae Borealis class has had the misfortune to be somewhat loosely defined as including stars that become faint at irregular intervals, and has accordingly become a repository for all sorts of irregular variables, including some so ill observed that there is no justification for placing them in any class. It is difficult to imagine any stars more different from the type star than are X Persei and RX Puppis, but many writers put them in the same class. The R Coronae Borealis class, as commonly used, is no longer a natural one, and must be more narrowly defined if membership is to be anything more than nominal.

Leon Campbell[1] has summarized the properties of R Coronae Borealis itself as the criteria for membership in the class:

a. Fairly uniform brightness at maximum, which may persist for months or years, and is the normal brightness of the variable.

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[1] Unpublished; kindly communicated to the authors.

b. Decrease in brightness over three magnitudes, usually sudden (taking place in a few days).

c. Recovery of brightness in general slower than fall (occupying months or even years), often irregular. When all the stars that conform to these definitions are compared, they are found to be similar in other properties also.

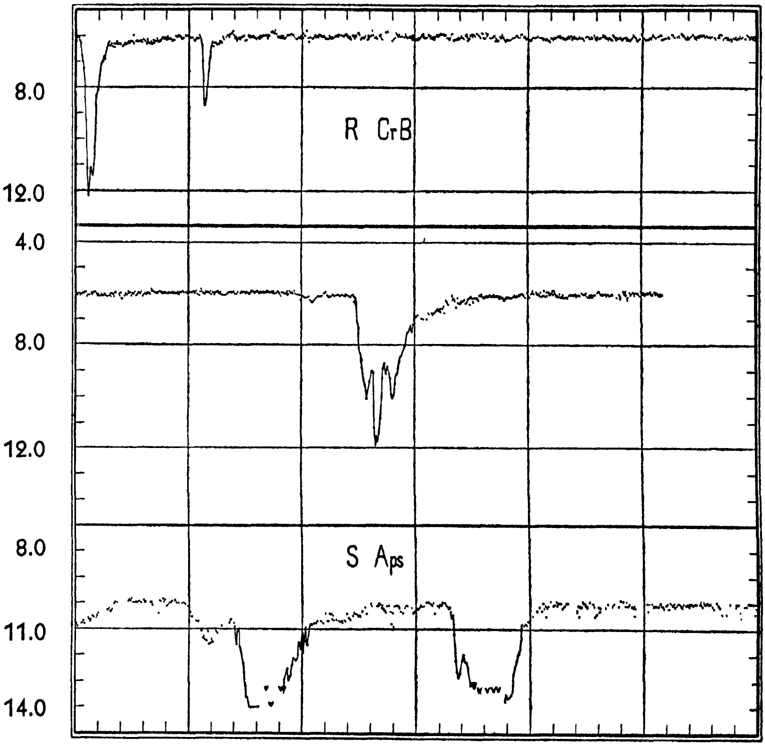

Figure X, 1.—Light curves of "R Coronae Borealis" stars:
R Coronae Borealis between J.D. 2423500 and 2429500
S Apodis between J.D. 2426000 and 2429000

The observations have been compiled from the work of the A.A.V.S.O. and other groups of observers by Mr. Campbell, who kindly permits us to reproduce the light curves.

TABLE X, I

VARIABLES ASSIGNED TO THE R CORONAE BOREALIS CLASS

Star	Max.	Range	Spect.	Type	Chap.
	m	*m*			
S Aps	10.0	5.2	R3	R CrB	X
SU Aqr	9.8	0.6	A2	Eclipsing	II
AB Aur	*7.2*	*1.2*	A0	Nebular	XI
Z CMa	8.4	3.1	Bp	Nebular?	XI
UV Cas	12.	3.6	m	R CrB?	X
UW Cen	*10.0*	*6.0*	K	R CrB	X
DY Cen	*12.0*	]*4.4*	..	R CrB	X
SY Cep	10.3	1.3	g2	Note 1	...
AE Cir	*12.2*	*3.8*	..	R CrB?	X
R CrA	9.7	3.8	Gpe	Nebular	XI
V CrA	9.0	]1.0	R0	R CrB	X
WX CrA	*12.2*	4.0	R5	R CrB	X
R CrB	5.8	]8.0	cG0ep	R CrB	X
SY Hyi	*13.4*	*2.1*	..	R CrB?	X
BR Lac	*13*	*3.5*	..	R CrB?	X
U Lup	*10.8*	*2.4*	G0	Semireg.	V
CQ Lyr	*13*	*2.5*	..	R CrB?	X
W Men	*13.8*	]*2.2*	..	Note 2	X
R Mon	9.3	4.7	Bp?	Nebular	XI
VY Mon	*13.7*	*2.2*	..	Nebular?	XI
Y Mus	*10.5*	*1.5*	..	R CrB	X
RT Nor	*11.3*	*5.0*	..	R CrB	X
TU Oct	*12.8*	*0.8*	..	Nebular?	XI
TX Oph	*9.6*	*1.6*	M0	Semireg.	V
XX Oph	*9.6*	*1.3*	Bep	Nebular	XI
V447 Oph	*9.5*	*4.0*	..	Note 3	
T Ori	9.7	3.1	..	Nebular	XI
EZ Ori	*11.5*	*1.5*	..	Nebular	XI
X Per	6.0	0.6	B0ne	Nebular?	XI
RX Pup	*11.1*	*3.0*	Pec.	Nova?	XI
V Pyx	*8.4*	2.6	K2	Semireg.	V
RS Sge	*12.0*	*2.5*	..	R CrB?	X
SV Sge	*10.8*	*3.7*	..	Note 4	
RY Sgr	6.1	5.9	G0ep	R CrB	X
GU Sgr	*11.0*	*2.8*	..	Note 5	X
W Sct	9.5	0.7	F?	Eclipsing	II
RT Ser	*9.2*	]*6.8*	cA8pe	Nova	VII
T Tau	9.0	3.8	Gpe	Nebular	XI
RY Tau	9.0	2.2	F8	Nebular	XI
SU Tau	9.5	]5.9	G0e	R CrB	X
RS Tel	*9.3*	]*3.7*	R8	R CrB	X
VV Tuc	*13.1*	*1.2*	..	Nebular?	XI
WY Vel	*9.2*	*0.9*	Map	Nebular; Note 6	XI
RZ Vul	*12.7*	]*4.3*	..	Long period? Note 7	
WW Vul	*10.2*	*0.9*	..	Eclipsing?	II
M3, Bailey No. 95	*13.2*	*1.6*	Ke:	Long period, Note 8	

NOTES

1. Evidence inconclusive.
2. Extragalactic; see Table X, IV.
3. Perhaps like XX Ophiuchi; Morgenroth, A.N., 254, 367, 1934; Seliwanow, Tash. Obs. Circ., No. 33, 1934; *ibid.*, No. 43; Hoppe, A.N., 254, 367, 1934.
4. Inconclusive; perhaps a long-period variable.
5. See Table X, III.
6. Resembles AX Persei (see Table XI, II).
7. M. and G. Wolf, A.N., 170, 366, 1905; Koyama, Kyoto Bul. 222, 1931 (R Coronae Type); Parenago, N.N.V.S., 4, No. 9, 303, 1934 (long-period variable).
8. Guthnick (Sitzber.d.Preuss.Ak.d.Wiss., Phys.-Math. Kl., 300, 1934) considers the star either a red irregular variable or a variable of the R Coronae Borealis class, having rejected his earlier surmise that it is an eclipsing star resembling ζ Aurigae (Sitzber.d.Preuss.Ak.d.Wiss., Phys.-Math. Kl., 24, 1933). The color indices at maximum and minimum are respectively +1.58 and +1.73. If we adopt Shapley's modulus for Messier 3 of $15^m.43$ (Star Clusters, 225, 1930), the absolute magnitude at maximum is —2.23 (photographic) or —3.81 (visual). The spectrum (Sanford, Pop. Astr., 27, 99, 1919) is of late type, with bright hydrogen lines, apparently variable in intensity. A second spectrum, secured when the variable was fainter, did not show the hydrogen lines. Shapley (Star Clusters, 50, 1930) considers the star a member of the cluster, and likens it to α Orionis in behavior. Recently it has been shown by Greenstein (H.B. 901, 1935) that 136 photographic observations, spread over forty years, can be represented by a period of 103.19 days. There is, however, a large scatter of the observations; and three observations of Larink are in complete discordance with the period. Thus the periodicity of the variable requires further substantiation.

Forty-five stars have been assigned to the class by various authors during the last decade, and Table X, I contains a list of them. The last two columns of the table indicate the authors' final decision as to the type of the star, and the number of the chapter in which that type is discussed in detail. After the selection has been made, there remain eleven galactic stars that are members of the class as defined in the previous paragraph, and six that are probably members, though the evidence is insufficient for a final decision.

48. General Properties of R Coronae Borealis Stars.—i. *Distribution.*—The stars of Table X, II have an average galactic latitude of 14°, and are therefore somewhat concentrated to the galactic plane; the omission of the high latitude sixth magnitude stars, R Coronae Borealis and RY Sagittarii, reduces the mean galactic latitude to 9°. We have thus an indication of high luminosity for the group.

TABLE X, II

GALACTIC VARIABLES OF R CORONAE BOREALIS CLASS

Star	Designation	1	b	Max.	Range	Spect.	Remarks	Ref.
				m	m			
S Aps	1459*71*	282°	—12°	10.0	5.2	R3	Maximum light variable.	1
UW Cen	1237*53*	268	+ 7	*10.0*	]*6.0*	K:		2
DY Cen	1319*53*	275	+ 7	*12.0*	]*4.4*	..		3
V CrA	1840*38*	325	—16	9.0		R0	Unpublished photographic observations.	4
WX CrA	1802*37*	323	—10	*12.2*	*4.0*	R5		5
R CrB	154428	14	+50	5.8	]8.0	cG0ep	Carbon lines strong in spectrum.	6
Y Mus	1259*64*	272	— 3	*10.5*	]1.5	..		7
RT Nor	1615*59*	295	— 8	*11.3*	5.0	..		8
RY Sgr	1910*33*	333	—20	6.1	7.9	G0ep	Weak carbon bands in spectrum.	9
SU Tau	054319	164	— 7	9.5	5.9	G0e	Weak carbon bands in spectrum.	10
RS Tel	1811*46*	315	—15	*9.3*	]4.0	R8		11

REFERENCES

1. Light curve, Payne, H.B. 868, 1929; Campbell, H.C. 319, 330, 344, 354, 361, 376, 383.
2. Light curve from unpublished observations by Miss Leavitt.
3. Hoffleit, H.B. 874, 1930 (light curve unpublished).
4. Observations by S. Gaposchkin.
5. Light curve and spectrum, Miss Swope, H.B. 902, 1936.
6. Spectrum, Berman, Ap. J., 81, 369, 1935.
7. Light curve, Payne, H.B. 868, 1929.
8. Hoffleit, H.B. 884, 1931 (light curve unpublished).
9. Light curve, Campbell, H.C. 354, 1930; 361, 1931; 382, 1933; 395, 1934; spectrum, C. P. Gaposchkin, H.B. 903, 1936.
10. Light curve, Campbell, H. C., *op. cit.*, note 9; spectrum, C. P. Gaposchkin, H.B. 903, 1936.
11. Spectrum, C. P. Gaposchkin, H.B. 903, 1936.

There has been in the past a general opinion that the R Coronae Borealis stars are connected with galactic nebulae[2]; but it will be seen that the removal of objects like R Coronae Austrinae, T Orionis, and T Tauri from the list of these stars destroys the close correlation; for none of the stars of Tables X, II, and X, III is now supposed to be connected with nebulosity.

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[2] See Ludendorff, Handb.d. Astrophys., 6, 83, 1928.

TABLE X, III

VARIABLES PROBABLY OF R CORONAE BOREALIS CLASS

Star	Designation	l	b	Maximum	Range	Spectrum	Reference
				^{m}	^{m}		
UV Cas	225859	78°	− 1°	12.	3.6	m	1
AE Cir	143668	281	− 9	*12.2*	*3.8*	..	2
SY Hyi	021979	264	−38	*13.4*	*2.1*	..	3
BR Lac	221345	65	−10	*13.*	*3.5*	..	4
CQ Lyr	183932	30	+14	*13.*	*2.5*	..	5
RS Sge	195219	25	− 4	*12.0*	*2.5*	..	6

1. Ludendorff, A.N., 209, 281, 1919.
2. Hughes, H.B. 883, 1931.
3. Hughes, H.A., 90, No. 4, 172, 1935.
4. Hoffmeister, A.N., 236, 242, 1929.
5. Hoffmeister, A.N., 236, 239, 1929.
6. Baade, A.N., 232, 67, 1928.

TABLE X, IV

VARIABLES RELATED TO THE R CORONAE BOREALIS CLASS

System	Star	Maximum	Range	Reference
		^{m}	^{m}	
Galactic	GU Sgr	*11.0*	2.8	1
Large Magellanic Cloud	W Men	*13.8*	]2.2	2

1. Luyten, H.B. 852, 1927; diagram of light curve, which is not typical for a star of R Coronae class, but which nevertheless comes nearer to that type than to any other.
2. Luyten, H.B. 846, 1927; the changes of brightness are slower than for the normal R Coronae Borealis stars, but are similar in general type. If the star is a member of the Cloud, as seems probable, it has, as Luyten points out, an absolute photographic magnitude —3.5.

ii. *Luminosity.*—The R Coronae stars are not numerous enough to permit a good statistical determination of their absolute magnitudes. Both their low average galactic latitudes and the c-character shown by the spectra of the best observed indicate that they are giant stars. If the absolute magnitude of the atypical variable W Mensae furnishes any indication of luminosity for the group, it points to a value in the neighborhood of −5, which is not at all incompatible with the character of the spectrum of R Coronae Borealis. In other words, this group of stars is not very dissimilar to the Cepheids in luminosity and in surface brightness, and therefore (presumably) in mean density.

iii. *Spectra.*—The R Coronae Borealis stars appear to have a common spectral feature that may well be of very great importance in determination of the type of variability. It has long been a matter of comment[3] that spectral class R is commoner among this type of variable than would be expected from its general rarity. In fact the known variables with spectra of class R have all been assigned either to the present group, to the Cepheids, or to the long-period variables[4]. One of the prominent features of the class R spectrum is the presence of absorption bands (the Swan bands) of carbon compounds, almost certainly to be attributed to an excess of carbon, compared to the composition of the average stellar atmosphere[5]. Thus it was of the greatest significance that Berman was able to show that the lines of carbon, and also faint Swan bands, are prominent in the spectrum of R Coronae Borealis (class cG0ep), and that an excess of carbon atoms must be regarded as the cause[6]. It was further noted by one of the writers[7] that both RY Sagittarii[8] and SU Tauri[9] have spectra resembling that of R Coronae Borealis; and that moreover RY Sagittari actually shows the Swan bands, characteristic of class R, faintly at some phases. Thus it seems not improbable that all the stars of R Coronae Borealis class have more carbon in their atmospheres than the average star, and Berman[10] has suggested that this feature is responsible for their variation of brightness. In drawing this conclusion it must, however, be remembered that a number of long-period variables and two possible Cepheids have spectra of the same class.

49. Properties of Individual Stars.—The variations of light of the majority of the R Coronae stars seem to be completely irregular[11]; the declines in brightness occur suddenly and without regularity, and the minima differ widely in form, being at times highly asymmetrical (as with R Coronae Borealis in 1917-1918[12], and at other times showing remarkable symmetry (as with R Coronae Borealis in 1923, and again, but with a very different shape, in 1935[13]).

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[3] Payne, The Stars of High Luminosity, 245, 1930.

[4] See p. 126.

[5] Rosenfeld, M.N., **93**, 724, 1933.

[6] Ap. J., 81, 369, 1935.

[7] C. Payne Gaposchkin, H.B. 903, 1936.

[8] Mrs. Fleming, H.A., **56**, 210, 211, 224, 1912; Miss Cannon, Henry Draper Catalogue, Remarks.

[9] Mrs. Fleming, H.A., **56**, 209, 1912.

[10] P.A.S.P., **45**, 55, 1933; **46**, 60, 1934.

[11] Sterne, H.B. 896, 1935, has demonstrated this statistically for R Coronae Borealis.

Most R Coronae stars are very steady in light at maximum, and the type star remained of the same brightness from December 31, 1925 to October 27, 1934, without a break. An exception appears to be S Apodis, which is appreciably variable at maximum light, and which is also somewhat abnormal by showing indications of a periodicity of about a thousand days[14].

Our knowledge of the spectroscopic behavior of the R Coronae Borealis stars rests mainly on the studies of the type star that have been made at the Mount Wilson[15] and Lick[16] observatories. The spectrum at maximum[16] shows absorption lines typical of Class G, and resembles that of a Cepheid—in other words, it is that of a luminous star. At minimum many of the absorption lines characteristic of maximum light (for example lines of TiII) appear as bright lines. The lines of CaII appear as bright lines during the minimum, at first sharp, later broadened; the bright lines are shifted 20 km/sec relative to the dark lines. The bright lines were no longer visible when the star had risen to within four magnitudes of maximum brightness, and within two magnitudes the maximal absorption spectrum was again observed. It is especially notewothy that no measurable changes of radial velocity were observed[16].

Berman's detailed analysis of all the available maximal spectra places R Coronae Borealis, at least in this phase, among the variable stars whose line spectra are almost completely analyzed, along with δ Cephei and o Ceti and a very few others. He has shown that the Swan bands account for peculiarities noted by early observers, and that all the spectral abnormalities can be quantitatively accounted for by an excess of carbon. Further he calls attention to a slight variability of radial velocity at maximum light, which is not dissimilar to that shown by supergiants such as γ Cygni and δ Canis Majoris.

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[12] Shapley and Campbell, H.C. 247, 1923.

[13] Campbell, Pop. Astr., 44, 209, 1936.

[14] Payne, H.B. 868, 1929.

[15] Joy and Humason, P.A.S.P., 35, 325, 1923; Mt. Wilson Report, 234, 1922.

[16] Berman, *op. cit.*

In the face of the observation that the absorption spectrum of R Coronae Borealis changes little during the variation of light, it is difficult to ascribe the great changes of brightness to increasing absorption by the Swan bands. A similar problem is presented by long-period variables, where large changes of brightness may be unaccompanied by spectral variation[17]; and Betelgeuse has the same property[18]. Comparisons of visual and photogaphic light curves of RY Sagittarii suggest that it may, however, become somewhat redder at minimum; and this idea is supported by Innes' direct observations of color[19]. Such a reddening need not, of course, be produced by band absorption, but may be of a general nature[20].

The virtual constancy of radial velocity makes it difficult to ascribe the changes of brightness to changes of size, although it is true that to be crucial the velocities should be measured during the fall to minimum; and changes of temperature large enough to produce the observed effects seem to be ruled out by the smallness of the spectral changes. Eclipses in the usual sense would hardly be expected always to occur suddenly and to pass off slowly. Occasional sudden engulfments in (slowly dissipated) nebulosity were once held to be possible, but their likelihood is reduced by the conclusion that R Coronae Borealis stars are not particularly associated with visible nebulosity, and by the likelihood that the peculiar velocities of these stars (and therefore their velocities relative to nearby nebulosity) are small.

It may therefore be said that at present there is no satisfactory quantitative interpretation of the sudden large changes (average six magnitudes) shown by R Coronae Borealis stars; Berman's suggestion of a fall in temperature, accompanied by a sharp increase in absorption[21] and a consequent diminution of brightness, is probably the most satisfactory. But the changes of brightness of most of the cataclysmic variables present more or less unsolved problems.[22]

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[17] Merrill, Mt. W. Contr. 539, 1936.
[18] Sanford, Mt. W. Contr. 464, 1933.
[19] A.J., 20, 95, 1899.
[20] See, for instance, Wurm, Zs.f.Ap., 13, 179, 1936.

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[21] P.A.S.P., 45, 55, 1933; *ib.*, 46, 60, 1934.

[22] A theory recently developed by O'Keefe, which avoids some of the difficulties mentioned, is described in The Telescope (Vol. 5, 111, 1938).

E

EXTRINSIC VARIABLES

CHAPTER XI

VARIABLE STARS AND NEBULOSITY

Mchatsa tuchi, vyutsa tuchi,
Nyevedimkoyou luna
Osveschaet snyeh letuchi.
Mutno nyebo, notch mutna.
Mchatsa byessi roi za roiem . . .*

Pushkin

All the variable stars hitherto described are either intrinsic variables, or non-variable stars apparently changing in brightness for geometrical reasons. There remains a small but very interesting group of stars that lies in some senses between these two types of variable stars. That some variable stars are situated in nebulosity has long been known, and the suggestion that the nebulosity is responsible for the variability is not new. None the less, the interaction of stars and nebulosity is still very far from being completely understood, and the case of the variable star involved in nebulosity is therefore worth presenting in some detail. Possibly some of the variables now to be mentioned actually belong to the classes of variable stars already described. But the variables in nebulae have also some characteristics peculiar to themselves.

50. Variable Stars in Nebulosity.—A list of the variable stars that are connected with nebulosity would be long and difficult to compile. Connection with extensive bright nebulosities can be established if there is some way (direct or indirect) of deciding that star and nebula are at equal distances from us: the relation of the Trapezium to the Orion nebula

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*The clouds turn, the clouds churn,
An unseen orb
Shines through the flowing murk.
The sky is gloomy, the night is dark,
The little devils swarm and swirl . . .

exemplifies the first; that of Nova Persei to the expanding nebulosity seen soon after its outburst, the second. If the bright nebulosity is smaller, the case becomes more complicated; and in passing through the planetaries to objects like B.D.+30°3639 it is difficult (perhaps meaningless) to distinguish nebulae from stellar envelopes. To show that a variable is associated with dark nebulosity is more difficult still: there are few cases in which the identification would be justified for a single star, and thus, although there are probably many single stars whose variations are caused in this way, we must confine ourselves at present to groups of variables that can be associated with dark nebulosity by a knowledge of common distance and similarity of variations.

In the following paragraphs we shall describe briefly a few typical associations of stars with nebulae. The arrangement is, as far as possible, by spectral classes of stars.

The Orion Group.—The faintest star of the Trapezium[1], BM Orionis, was at first regarded as an eclipsing star[2]; but like the very similarly situated TY Coronae Austrinae (*q.v.*) it seems now with little doubt to be an irregular variable embedded in nebulosity. The integrated spectrum of the four Trapezium stars is given as Oe5 in the Henry Draper Catalogue; Hubble[3] classes them as Oe5—BO, Aitken[4] gives for the spectra: A, B5p; B, B2p; C, B3 (Mount Wilson), and Baade and Minkowski[5] give for components A, B, C and D of the Trapezium the spectral classes B1, B6, O7, and B1; BM Orionis is component B. Not only is it the faintest, but also it appears from the color excesses tabulated by Baade and Minkowski to be the most reddened of the four. It is apparently a typical variable imbedded in nebulosity.

The star BM Orionis is the brightest of a very large group of irregular variables, all situated in or near the confines of the Orion Nebula (here understood to include the bright emission nebulosities in and near N.G.C. 1976 and 1982). Sixty definitely known are given by Brun in his paper; in addition, a number of others are suspected of variability. They are closely crowded; seven appear on the large-scale photograph published by Baade and Minkowski: AK, AC, AF, BM, AD, AE, and TU Orionis. The variables are probably associated in space with the nebula; the apparent association in the sky, though suggestive, is not final on this point, but the additional fact that all the stars are varying in similar, irregular fashion strengthens the case. In spite of intensive studies (made very difficult by the nebulosity and by the faintness of many of the stars) no satisfactory period has ever been found for any of the variables near the Orion nebula.

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[1] See Brun, Publ. Lyons Obs., 1, 7, 10, 1935, for a general account of the region, and charts of the variables connected with the Orion nebula; see Burnham, General Catalogue of Double Stars, Vol. 2, p. 427, for chart of the Trapezium.

[2] See p. 30.

[3] Mt. W. Contr. 241, 23, 1922.

[4] New General Catalogue of Double Stars, 1, 358, 1932.

[5] Mt. W. Contr. 572, 1936.

Unfortunately, few of the Orion variables are bright enough to be studied spectroscopically; but the star H.D. 37061, the central star of N.G.C. 1982, found to be variable by Jacchia[6], is of about the seventh magnitude, and has a spectrum of Class B*. Possibly BN Orionis, spectrum A7, is also associated with the group.

The distance of the Orion nebula is reasonably well known, and if we adopt for it a modulus of 5.9 magnitudes, we can deduce the absolute magnitudes of the variables, uncorrected of course for obscuration. The absolute visual magnitudes thus derived run from +2.3 (BM Orionis at maximum) to about +9 for faint stars like AC, BP, BT, and CE Orionis. Even if we allow for an absorption of three to five magnitudes by the nebula (which is high, when we recollect that the variables are presumably within the nebula, some of them probably not deeply embedded), all these stars appear as members of the Main Sequence, with a probable mean absolute visual magnitude of about +5.

That the Orion variables are within, and caused to vary by, the nebulosity, and that they are members of a Main Sequence with quite irregular variations, were pointed out long ago by Shapley.[7] Thus, by position in the Russell diagram, and in the nature of their variations, the Orion variables stand apart from most stars that we have hitherto discussed. Although they are the best known and most extensive group of nebular variables, a number of other groups are known (see the Pleiades, TY Coronae Austrinae, R Monocerotis, AG Carinae, in the present section).

The relation of the spectrum of a nebula to that of the exciting star is complicated in the Orion nebulosities by the presence of a number of potentially exciting stars with a considerable range in spectrum and brightness. In a book which (like the present) attempts to avoid theoretical discussions until sufficient material is collected, it would be inappropriate to consider the problem, although it is certainly closely bound up with the question of the state of the nebular material, and the consequent influence of the nebula on the light of the stars, or even on the stars themselves. Because BM Orionis is the faintest member of θ_1 Orionis, we cannot learn very much about it from the spectrum of the Orion nebula; but we can learn much about the environment in which it and the other Orion variables are placed from the spectra of the Orion nebulosities.[8]

The Carina Group.—The spectrum of AG Carinae, H.D. 94910, is of P Cygni class with bright lines of hydrogen and neutral helium. It is the brightest of a group of four variables, all situated close together in a region of dark nebulosity. It varies slowly and irregularly with a range of two magnitudes[9]. Of identical spectrum is the neighboring *GG Carinae*, H.D. 94878, which, however, is a periodic variable, perhaps an eclipsing star. Although the period is constant, the range and shape of the light curve are variable[9]. The star *T Carinae*, also associated with the group, is apparently a normal K0 star of constant radial velocity; it shows slow, irregular variations of small range. The fourth associated variable, *ES Carinae*, varies irregularly, though a minimum suggesting eclipsing type was observed by Hertzsprung[10], who suggested that it furnishes a possible example of an eclipsing system with one component intrinsically variable. Mrs. Greenstein, from the Harvard plate material, concluded that the star does not appear to be an eclipsing star.

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[6] Bologna Publ., 2, 173, 1933.

*The spectrum is given in the Henry Draper catalogue as B8, but the residuals are large, and a re-examination indicates that it is nearer to the first observation, B5. The spectrum is given by Hubble as B1p (4686 strong for the type). Harvard plates confirm the variability of the star, but the brightness of N. G. C. 1982 makes estimation difficult.

[7] H. C. 254, 1924.

[8] See Hubble, Mt. W. Contr. 241, 1922; Greenstein and Henyey, Ap. J., 87, 79, 1938.

The above small group of variable stars is probably associated with the small dark nebula mentioned by Mrs. Greenstein—no doubt also associated with the more extensive nebulosities that pervade the whole constellation of Carina, being most conspicuous in the neighborhood of the "keyhole nebula" (probably illuminated here by the well-known group of Wolf-Rayet stars). It is noteworthy that the nova η Carinae[11] appeared near, possibly within the same nebula. In the district near the four other variables just described there seems to be no *bright* nebulosity. If we assume that the dark nebula is at the same distance as the bright nebula near the "keyhole," with a modulus of $10^m.6$, the absolute photographic magnitudes of AG, GG, and T Carinae (uncorrected for obscuration) are —2.6, —0.9, and —3.2. On the same basis, ES Carinae seems to have an absolute photographic magnitude of about +3. The magnitudes for the P Cygni stars are reasonable; T Carinae must be very bright.

The Monoceros Group.—Associated with the well-known variable nebula N.G.C. 2261, R Monocerotis is slightly variable. The spectra of star and nebula are similar, and have "nova characteristics"[12]. The bright lines tabulated by Slipher are principally permitted lines of FeII. Merrill places the star among the Be stars with bright iron lines[13]. The star and the variable bright nebula are probably associated with the nearby bright nebulae N.G.C. 2245 and N.G.C. 2247, both of which contain stars that seem to be slightly variable[14]. We consider them also associated with the dark nebula near N.G.C. 2264, in connection with which Wolf[15] discovered a number of faint variable stars. On the basis of an adopted modulus of $10^m.9$ for the nebulosities, R Monocerotis has an absolute photographic magnitude of —1.6, and Wolf's variables range from +3 to +5.5, recalling the group in Orion.

AE Aurigae.—The star, of Class B0p (Aitken 3843, $6^m.7$, $10^m.0$?, distance $8''.4$), is associated with the bright nebula I.C. 405; the spectrum of the latter shows a continuum on which bright hydrogen and OIII lines are

[9] N. K. Greenstein, H. B. 908, 1938.
[10] Hertzsprung, B. A. N. 77, 1925.
[11] See p. 265.
[12] V. M. Slipher, Lowell Bul. 81, 1918.
[13] Ap. J., 65, 291, 1927.
[14] Harvard observations; see also Pease, Mt. W. Contr. 186, 1920.
[15] Wolf, A. N., 221, 379, 1924.

superimposed[16]. The variations seem to be irregular, though a six-month period has been suggested[17].

γ *Cassiopeiae.*—The spectrum (Class B0pe) has been known to be variable for some time; Lockyer suggested a four-year period in 1933. Between 1929 and 1936, considerable changes took place in the radial velocity, the total intensity of bright lines, the intensity ratio of bright components, and the separation of the bright components[18]; it is not possible to give details in this place. Of the four effects mentioned, the first and last are probably factitious, being caused by the second and particularly the third. In 1935 and 1936 there were unprecedented spectral changes, which McLaughlin attributed to the outflow of the atmosphere. In June 1936 the star suddenly grew brighter by half a magnitude[19], a large change for a star of this type[20].

The two bright nebulae I.C. 59 and 63 are connected with γ Cassiopeiae[21]; they are fan-shaped, and their spectra show bright lines of hydrogen and [OIII].

The Pleiades.—Probably the best known of all groups of stars involved in nebulosity, the Pleiades provide several more or less definite evidences of variability. The nebula that surrounds them shows an absorption spectrum, but one that seems to alter with distance from the illuminating stars[22].

Electra (17 Tauri, H.D. 23302) has not been reported to be variable. *Asterope* (18 Tauri, H.D. 23489) has apparently a normal A0 spectrum; Hopmann[23] reported a change of three-tenths of a magnitude from visual estimates; Strassl, on the other hand, found no change of brightness from a spectrophotometric study[24]. *Maia* (20 Tauri, H.D. 23408) is not appreciably variable during the interval studied[25]; it was placed by Henroteau with the β Canis Majoris group; but we do not consider it to be a member[26]. *Merope* (23 Tauri, H.D. 23480) has at present the most striking bright-line spectrum of all the Pleiades, and is associated with the brightest nebulosity. No variation of its brightness has been noted. *Taygeta* (q Tauri, H.D. 23338) has an apparently normal B5 spectrum; variability has been suggested by Güssow[27]. *Alcyone* (η Tauri, H.D. 23630) is at present the brightest of the Pleiades; although recently no variation has been noted, some early discussions were considered to have shown that Alcyone was once not so bright as it is at present[28]. *Atlas* (27 Tauri, H.D. 23850) has not been observed to vary; the spectrum is apparently normal. *Pleione* (28 Tauri, H.D. 23862) is the most striking variable of the Pleiades, although it is neither the brightest, nor the most obviously involved in nebulosity. The spectrum has displayed marked changes; bright lines, visible in 1889 and 1895, had disappeared in 1904[29]. The star itself is supposed to have been variable in earlier times[30]. A diminution of brightness has recently been noted by Calder[31].

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[16] Hubble, Mt. W. Contr. 241, 12, 1922; Vorontsov-Velyaminov, New Stars and Galactic Nebulae, 114, 1935.

[17] Parengo and Kukarkin, N. N. V. S., 3, 30, 1930; 3, 90, 1931; see Tschernow, N.N.V.S., 2, 62, 1930.

[18] W. J. S. Lockyer, M. N., 93, 619, 1933; *ib.*, 95, 520, 1935; *ib.*, 96, 2, 1935; ib., 96, 679, 1936; Heard, Ap. J., 81, 341, 1931; Cleminshaw, Ap. J., 83, 495, 1936; McLaughlin, Ap. J., 84, 235, 1936.

[19] Baize, L'Astronomie, 50, 395, 1936.

[20] See page 324.

[21] Hubble, Mt. W. Contr. 241, 1922.

[22] Greenstein and Henyey, Ap. J., 87, 80, 1938.

[23] Veröff. Univ. Leipzig, 3, 24, 1932.

[24] Zs. f. Ap., 5, 205, 1932.

[25] Guthnick and Pavel, A. N., 215, 397, 1921.

[26] See page 188.

[27] VJS., 60, 65, 1925.

The Corona Austrina Group.—Seven variables, as enumerated in Table XI, I are involved in the dark patch of nebulosity in the constellation Corona Austrina. All are irregular in their variations[32]. Two of them (TY Coronae Austrinae and R Coronae Austrinae) are connected with bright portions of the nebulosity, presumably illuminated by themselves. The two nebulae (N.G.C. 6729 and 6726) have continuous spectra, and the stars seem, respectively, to be of Class B or A, and of Class G, peculiar, with bright lines. The connection between R Coronae Austrinae and the nebula N.G.C. 6726, at whose tip it is situated, is very intimate; both are variable in brightness, the changes in the nebula suggesting lights and shadows (as from an intermittently obscured source) passing across a nebular background[33]. Full details are given in the paper just quoted[32]. There is little doubt that the variations are caused by the nebulosity; but the exact process has yet to be analyzed. The pattern of the nebulosity itself is invariant, and illumination sweeps across it. But this illumination does not proceed in radial waves, even after allowance for perspective effects. It follows that the light of the illuminating star is obscured in some directions and not in others, presumably by drifting clouds of some sort, and that we see the shadows crossing the nebula (plus effects depending on the light-time)[34].

T Tauri.—The classical case of association of a variable star with a variable nebula (N.G.C. 1555)[35], T Tauri strongly resembles R Coronae Aus-

[28] Miss Agnes Clerke, *The System of the Stars*, 222, 1890.

[29] H. A., 91, 389, 1918.

[30] See Wolf, Ann. Paris Obs., 14, 26, 1877; Pickering, A. N., 123, 95, 1889.

[31] See The Telescope, 4, 73, 1937; H. A. 105, 453, 1937; the comparison with the sharp-lined spectrum of P Cygni is perhaps misleading; Pleione always showed a spectrum with wide, hazy lines, as do the other Pleiades. The bright lines have recently reappeared (H.A.C. 465, 1938); as with μ Centauri, the reappearance went with diminution of light (Gerasimovič, H.B. 854, 1928).

[32] S. Gaposchkin, H. A., 105, No. 27, 1936.

[33] Hubble, Mt. W. Contr. 241, 12, 1922; Mt. W. Rep., 252, 1921; V. M. Slipher, Lowell Bul. 81, 1918.

[34] For this remark we are indebted to Professor H. N. Russell.

[35] Auwers, M. N., 22, 150, 1861; Hind, M. N., 24, 65, 1863; Burnham, M. N., 51, 94, 1891; Barnard, M. N., 55, 442, 1895; *ib.*, 56, 66, 1896; Keeler, M. N., 60, 424, 1900; Burnham, M. N., 61, 94, 1901; d'Arrest, M. N., 56, 328, 1861; O. Struve and Winnecke, A. N., 57, 207, 1862; Schmidt, A. N., 57, 243, 1862; Schönfeld, A. N., 69, 246, 1867; O. Struve and d'Arrest, A. N., 71, 143, 1868; Pease, Ap. J., 45, 89, 1917; Merrill, Ap. J., 65, 289, 1927; Adams and Pease, P. A. S. P., 27, 32, 1915; Sanford, P. A. S. P., 32, 59, 1920; van Maanen, P. A. S. P., 38, 326, 1926; Hubble, Mt. W. Rep. 252, 1921; *ib.*, 222, 1922; "the only absolutely authentic variable nebula", Curtis, P. A. S. P., 27, 242, 1915.

trinae. The star varies irregularly; very small changes in the brightness of the nebula have recently been recorded by Hubble, no great change taking place in the star during the same interval. The spectrum has been variously classified as F5e (Miss Cannon); Fpe (Pease); Gpe (Hubble); Me (Adams); "like +30°3639" [= W] (Vorontsov-Velyaminov). The spectrum is compound, consisting of well-defined bright lines on a dark line spectrum of Class F5[36]; elsewhere it is described as of Class F5, surrounded by an extensive atmosphere that shows the Wolf-Rayet lines[37]. Merrill[38] gives the spectrum as Gpe, and enumerates bright iron lines. Sanford[39] finds both dark and bright iron lines, and notes a resemblance to η Carinae. Miss Cannon notes that the spectrum is very peculiar, with bright lines of hydrogen, ionized calcium, and ionized strontium (4077).

RY Tauri.—The irregular variable RY Tauri illuminates the southern end of the dark nebula Barnard 214[40]. Its spectrum is given at Mount Wilson as of Class F8±; Miss Cannon states: "seen on several plates, but very hazy and indistinct. In general G-G5, and the line 4097 strong". Collins finds a fairly high color index ($+0^m.93$) for RY Tauri. So far as the evidence goes, the system of star and nebula resembles that of T Tauri. Parenago[41] assigns the star to the R Coronae Borealis group, but for the reasons given in the chapter that deals with those stars, we have not included it with them.

R Aquarii.—Although the variable is described in the chapter dealing with long-period variables, it must be included in any list that contains variable stars associated with nebulosity. R Aquarii is with little doubt a multiple object, consisting of a long-period variable and a variable blue companion, both associated with nebulosity[42]. The association of red giants with nebulosity may in fact be commoner than is now generally recognized[43].

The stars and groups of stars just enumerated are collected in Table XI, I.

The variables enumerated in Table XI, I are of spectral classes ranging from O to M, including some definitely peculiar spectra, and one or two bright line stars of early type. Though far from complete, the list is probably representative. The absolute magnitudes range from about —4 for AG Carinae to about +9 for a few stars near the Orion nebula. Even if a reasonable allowance of three or four magnitudes is made for

[36] Adams and Pease, P. A. S. P., *27*, 132, 1915.

[37] Mt. W. Rep., 1915.

[38] Ap. J., 65, 289, 1927.

[39] P. A. S. P., 32, 59, 1920.

[40] Nielsen, A. N., 239, 223, 1930; see Collins, Ap. J., 86, 552, and Plate XXII, 1937.

[41] N. N. V. S., 3, 229, 1932.

[42] See page 123.

[43] Compare Struve, Elvey, and Roach, Ap. J., 84, 299, 1936 (nebula associated with Antares).

TABLE XI, I

VARIABLE STARS ASSOCIATED WITH NEBULOSITY

Nebula	Spectrum	Associated Stars			
I.C. 59, 63	H, [OIII]	γ Cas	005060	B0ne	
Pleiades	Cont.	18 Tau	HD23489	A0	
		q Tau	HD23338	B5	
		28 Tau	HD23862	B8n(e)	
N.G.C. 1555		T Tau	041619	Fpe	
B 214		RY Tau	041528	F8:	
I.C. 405	Cont., H, [OIII]	AE Aur	050934	B0p	
Orion (N.G.C. 1976, N.G.C. 1982, etc.)	Cont., H, [OIII], etc.	T Ori	053005	AK Ori	053005
		RZ Ori	052805	AL Ori	053004
		SU Ori	052904	AM Ori	053005
		SX Ori	052904	AN Ori	053005
		SY Ori	053604	AO Ori	053005
		SZ Ori	053005	AP Ori	053005
		TT Ori	053004	AQ Ori	053005
		TU Ori	053005	AR Ori	053005
		TV Ori	053005	AS Ori	053104
		VW Ori	052805	AU Ori	053106
		VX Ori	052804	AX Ori	053106
		VY Ori	052805	AZ Ori	053105
		VZ Ori	052805	BC Ori	053105
		WW Ori	052905	BM Ori	053005
		WX Ori	052905	BO Ori	053004
		WY Ori	052905	BP Ori	053205
		WZ Ori	052905	BS Ori	052804
		XX Ori	052906	BT Ori	052904
		XY Ori	052905	BV Ori	052904
		XZ Ori	052905	BX Ori	053005
		YY Ori	052906	BY Ori	053004
		YZ Ori	052905	BZ Ori	053005
		ZZ Ori	053005	CC Ori	053004
		AA Ori	053005	CD Ori	053004
		AB Ori	053005	CE Ori	053005
		AC Ori	053005	CF Ori	053005
		AD Ori	053005	CH Ori	053104
		AE Ori	053005	EZ Ori	052905
		AF Ori	053005	? RY Ori	052702
		AG Ori	053005	? UX Ori	045903
		AH Ori	053005	? BF Ori	053206
		AI Ori	053005	? BN Ori	053106
N.G.C. 2245	Cont.	Anon.			
N.G.C. 2247	Cont.	Anon.			
N.G.C. 2261	Cont., faint bright lines	R Mon	063008	Bp	
N.G.C. 2264	..	4.1924 Mon to 23.1924 Mon			

TABLE XI, I—*Continued*

Nebula	Spectrum	Associated Stars		
N.G.C. 3372	H, [OIII]	η Car	104159	Feq to Q pec
		AG Car	105259	Beq
		GG Car	105259	Beq
		ES Car	110659	..
N.G.C. 6726	Cont.	R CrA	185537	Gpe
		S CrA	185437	
		T CrA	185537	
N.G.C. 6729	Cont.	TY CrA	185437	B9:[46]
		VV CrA	185637	
		DG CrA	185537	
		Knox-Shaw 15[47]		
		Also:		
		HD	176269	B8 Not variable
		HD	176279	B8 Not variable
		HD	176386	A0 Not variable
I.C. 1318	Cont., H, [OII][48]	γ Cygni		cF8 Light and radial velocity variable[49]
N.G.C. 7000	H, [OII], [OIII], Cont.	α Cygni		cA2 Light, radial velocity and spectrum variable[50]
	??	R Aquarii[51]	233916	

obscuration, most of the stars appear to belong to the Main Sequence of the Hertzsprung-Russell diagram. R Aquarii is, of course, a giant star; but as such its behavior is regular, and interest centers rather around the (hypothetical) blue com-

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[44] Pease, Mt. W. Contr. 186, 1920.

[45] Perrine, L. O. B., 1, 187, 1902; Pop. Astr., 10, 494, 1902.

[46] For discusssion of spectral classification, see Gaposchkin, H. A., 105, No. 27, 1936.

[47] Helwan Bul., No. 20, 1922.

[48] Greenstein and Henyey, Ap. J., 86, 620, 1937.

[49] Güssow and Guthnick, Kl. Veröff., Ber.-Bab., No. 8, 1930; star No. 416.

[50] Güssow and Guthnick, *op. cit.*, Star No. 419; see also Table XI, III.

[51] Lampland, Pop. Astr., 30, 162, 1922; *ibid.*, 619, 1922; the "nebular spectrum" discussed in the study of R Aquarii (see, for instance, Merrill, Mt. W. Contr. 513, 1935) is not that of the outer lenticular nebulosity, which has never been observed, though it may well resemble it.

panion, which is without doubt also variable in a slow and irregular manner[52], recalling the light curve of AG Carinae.*

There can now be little doubt that a number of stars closely associated with, and probably involved in, nebulae are varying in a truly irregular manner. There are a number of other irregular variables of similar behavior, not visibly associated with nebulosity. It is noteworthy that many of these stars show the spectroscopic mark of nebulosity, for their spectra contain forbidden lines. A list of irregular variables with this characteristic is given in Table XI, II.

Two groups of variable stars† whose spectra show forbidden lines have been omitted from Table XI, II: the few long-period variables with forbidden iron lines at minimum[53]; and the true novae[54]. There are in addition six stars, with forbidden lines recorded in their spectra, that are not now known to be variable. They are enumerated in Table XI, III, and would furnish an interesting group of objects to be narrowly examined for variability.

Probably the most instructive way of comparing the stars given in the foregoing tables lies in a comparison of their light curves, and it is then seen that they fall into three main groups. The first contains a number of stars that vary in an erratic manner, and all their light apparently emanates from one varying object: T Orionis, T Tauri, R Monocerotis, R Coronae Austrinae, and probably most of the variables in Orion and Monoceros. Possibly W Cephei and XX Ophiuchi are also members of this group. The second group consists of stars that show evidence of duplicity—they appear to be systems consisting of a red star, accompanied by a blue star, one or both of which may be varying. The stars R Aquarii, Z Andromedae, CI Cygni, AX Persei, RW Hydrae, and WY Velorum, appear to belong to this group. The stars Z Canis

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[52] Merrill, Mt. W. Contr. 513, 19, 1935.

*It should, however, be remembered that the blue companion to Mira Ceti, not known to be associated with nebulosity, is also definitely variable with "long or irregular period" (see Joy Mt. W. Contr. 311, 1936; van Biesbroeck, Publ. Yerkes Obs., 5, 191, 1927).

†Planetary nebulae are of course excluded, although the distinction between them and some of the stars tabulated is perhaps rather artificial.

[53] See p. 122.

[54] See Chapter VII.

TABLE XI, II

IRREGULAR VARIABLE STARS WITH SPECTRA SHOWING FORBIDDEN LINES

Star	Designation	Magnitude Max.	Magnitude Amp.	Spectrum	Forbidden Lines	Remarks
Z And	232848	8.3	4.5	M + Ocp	OIII, NeIII	Probably two stars
R Aqr	2338*15*	5.8	5.0	M + Be	OIII, NeIII, SII, 4658	Probably two stars, one is long per. var.
AE Ara	1733*47*	*11.6*	*2.2*	Pec.	?	?
Z CMa	0659*11*	8.4	3.1	Bp	FeII	Nova?
η Car	1041*59*	—0.6	8.5	Feq	FeII, SII	Nova
W Cep	223257	6.9	1.7	Mp	FeII	Possibly two stars
VV Cep	215363	4.9	0.8	M2ep	FeII, SII	Two stars; eclip. sys.
CI Cyg	194635	*10.5*	*2.7*	Ocp	OIII, FeII	Probably two stars
WY Gem	060523	*7.4*	0.5	M3ep	FeII, SII?	Possibly two stars
RW Hya	1328*24*	*9.7*	*1.2*	K8ep	OIII	Long period var.
SY Mus	1127*64*	*11.3*	*0.9*	Pec.	?	Long period var.?
XX Oph	1738*06*	*9.6*	*1.3*	Bep	FeII	?
AG Peg	214612	6.3	1.4	Pec.	FeII, NII	Nova?
AX Per	013053	*9.4*	*4.0*	M + Pec.	OIII, NeIII	Probably two stars
RX Pup	0810*41*	*11.1*	*3.0*	Pec.	OIII, NeIII	Nova?
RY Sct	1819*12*	9.3	0.6	Pec.	NII* AIV, unidentified	Eclipsing star
W Ser	1804*15*	*8.9*	*1.1*	cG2.5v	FeII	Eclipsing star
RT Ser	1734*11*	9.2	]6.8	cA8pe	OIII	Nova
WY Vel	0918*52*	*9.2*	*0.9*	Map	FeII	Possibly two stars

* Unpublished; kindly communicated by Merrill.

TABLE XI, III

ADDITIONAL STARS WITH FORBIDDEN LINES IN THEIR SPECTRA

Star HD	Position				Mag.	Spect.	Forbidden Lines	Remarks
	h	*m*	°	′	*m*			
45677	6	23.7	—13	0	7.5	B0p	OI, FeII	Mrs. Fleming, H.C. 32, 1898; Merrill, P.A.S.P., 37, 163, 1925; Mt.W. Contr. 355, 1928.
50138	6	46.7	— 6	31	6.6	B9	OI	Merrill, Mt.W.Contr. 423, 1931.
60414,5	7	29.2	—14	18	5.2	M2ep	FeII	Adams, Joy, and Humason, P.A.S.P., 37, 161, 1925; H.D. spectrum, K5 + B.
167362	18	9.7	—30	54	10	Pec.	FeII, OIII	Miss Cannon, H.C. 224, 1921.
......	18	25.2	— 6	4.8	..		OI	Merrill, P.A.S.P., 43, 411, 1931.
203338,9	21	16.5	+58	12	5.9	K5p	FeII	Adams, Joy, and Humason, P.A.S.P., 37, 161, 1925; H.D. spectrum, K0 + A0, star a visual double.

Majoris and RX Puppis, although spectroscopically they belong to the first group, differ from the rest of the members in the slowness and steadiness of their light changes. Finally there is the peculiar star W Serpentis, at present assigned to the eclipsing group, which shows the forbidden lines of ionized iron at minimum, as does also the other peculiar eclipsing star VV Cephei. The stars of Table XI, III, are very similar to those of Table XI, II in everything except variability, and, especially for the objects whose spectroscopic peculiarities are attributable to duplicity, there is no reason to expect that all such systems should vary in brightness, although their high luminosity and low density might predispose to variability.

51. Analysis of Nebular Variables.—The preceding section contains data on a number of objects with a wide range of properties, which, although they are linked together by spectroscopic similarities, and have something in common when their variations are compared, are not a single type of variable, like the Cepheids or the SS Cygni stars. They may in fact be classified into almost as many groups as the variable stars in general, although the resulting groups will not be the same as for normal variable stars.

The following subdivisions suggest themselves:

I. Extrinsic variables: single stars affected by nebulosity
    Examples: T Tauri, R Coronae Austrinae, T Orionis

II. Double Systems:
    i. Eclipsing Stars
        Examples: VV Cephei, RY Scuti
    ii. Binaries, not eclipsing
        Examples: Z Andromedae, R Aquarii

III. Intrinsic Variables:
    Examples: RX Puppis, AG Pegasi

In Group I the variations can probably be attributed almost entirely to obscuration by nebulosity. The details of the process have not been quantitatively worked out, but in a few years, when our knowledge of the constitution of galactic neb-

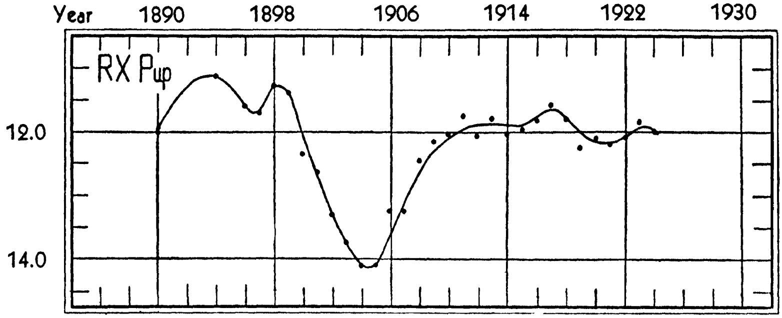

Figure XI, 1.—Light curve of RX Puppis, from photographic observations made on Harvard plates.

ulae is better than it is now, the necessary numerical data will permit the analysis. It will then be possible to decide whether variations such as those of R Coronae Austrinae can be produced geometrically by nebulosity of the existing constitution and motions. The peculiar spectroscopic behavior of the stars must also be satisfactorily understood in terms of their radiation and the immediate environment in which they are situated.

In Group II we encounter an even more interesting set of conditions. All these stars are considered by the writers to consist, like R Aquarii, essentially of three components: a late type star, which supplies the absorption spectrum; an early type star, which excites the forbidden line spectrum; and a nebula, in which the latter is produced. Whether the first and third of these are identical (the luminous, late type star of low density providing approximately nebular conditions in its outer atmosphere) is an interesting speculation; but as we shall see in examining the spectrum variables of Class B, it is sometimes difficult to decide where a stellar atmosphere leaves off. The atmospheres of novae and Wolf-Rayet stars would probably qualify after an interval as surrounding nebulosity. Certainly the members of Group II are all very luminous red stars. A possible subsection of Group II contains red stars that show forbidden lines of comparatively low excitation (W Cephei, W Serpentis); here again the red star may possess an atmosphere providing "nebular" conditions, but the exciting star must be postulated at a lower temperature than, for example, in Z Andromedae.

Group III contains but few objects; possibly when all the novae and true obscuration variables (RT Serpentis, XX Ophiuchi) have been removed it will be quite depopulated. A few possible survivors are discussed in the next section.

The extrinsic variables have been surveyed in the first part of the chapter, and the spectra of the few that are bright enough to study (T Tauri, R Coronae Austrinae) are there described.

The binary systems are represented by three eclipsing stars, for which the spectroscopic data will now be summarized.

VV Cephei.—An eclipsing system with a period of 20.4 years[55] and spectra classified as M2+ B9, this star shows, in addition, the forbidden lines of [Fe II] and [S II]. The spectral peculiarities have long been known[56]. During the minimum the bright lines of hydrogen disappear almost if not quite completely, but the forbidden iron lines persist throughout, which shows that they are not formed in the atmosphere of the small, blue component. The spectral phenomena are complicated by the independent variability of the red component of the system. It is not possible to draw conclusions as to the sources of the various spectra or the intensities of the bright lines unless an absolute spectrophotometric study is undertaken, for the apparent intensity of the bright lines and of the blue end of the combined spectrum must depend very much on the intensity of the (inseparable) red component. The conclusion of Kukarkin and Parenago[57] that the star is "nova-like" must be abandoned in view of the accordance of photometric and spectroscopic data in making VV Cephei an eclipsing star.

RY Scuti.—An eclipsing star, resembling β Lyrae.[58] The spectrum shows little excepting bright lines at 4658 (CIV?), 4701 [AIV]?, 4733 [AIV]?, and 4768, hydrogen, and helium[59] (identifications ours). Dr. Merrill kindly communicated to the writers that there is emission of [NII].

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[55] S. Gaposchkin, H. C. 421, 1937.

[56] Miss Cannon, H. A., 56, 101, 1912; *see* Adams and Joy, P. A. S. P., 33, 263, 1921; Humason, H. B. 767, 1922; Adams and Joy, P. A. S. P., 35, 328, 1923; Merrill, Humason, and Burwell, Ap. J., 76, 169, 1932; Adams, Joy, and Humason, Ap. J., 64, 237, 1926 (spectroscopic absolute magnitude —2.0, gM2ep); Lick Obs. Publ., 16, 320, 1928 (variable radial velocity); Harper, Publ. Dom. Ap. Obs., 6, 196, 1934; McLaughlin, Ap. J., 79, 380, 1934; Mount Wilson, unpublished (spectroscopic orbit); Christie, P. A. S. P., 50, 52, 1938.

[57] Kukarkin and Parenago, Stellar Variability, p. 234, 1937.

[58] S. Gaposchkin, H. A., 105, No. 27, 1936.

[59] Merrill, Humason, and Burwell, Mt. W. Contr. 294, 1924; Merrill, Mt. W. Contr. 294, 1925; *ibid.*, 349, 1928.

W Serpentis.—Eclipsing star with a very peculiar light curve.[60] Bright forbidden iron lines are shown at minimum; the spectrum[61] varies from cG2 to cG4.

There are five apparently double systems combining a late-type absorption spectrum with an emission spectrum of high excitation, showing forbidden (and permitted) lines.

Z Andromedae.—This system consists essentially of a bright line star of early type, a nebula, and a late type star. The two former were exhaustively discussed by H. H. Plaskett[62] for the interval preceding 1922; but the first recorded spectral classification[63] of Z Andromedae made it an M star, and even in 1922 the titanium oxide bands were discernible.[64] There can be little doubt of the presence of two stellar bodies; the semiperiodic outbursts[65] are apparently the work of the bluer star, and if the red component varies it does so inconspicuously. The possibility that the bright line spectrum is excited in the outer atmosphere of the red star should not be forgotten.

R Aquarii.—Already briefly mentioned among the variable stars visibly associated with nebulosity, R Aquarii presents an even more complex system than Z Andromedae.[66] The evidence points to the presence of an apparently normal long-period variable; a variable star of high temperature; a small "nebulosity" giving a variable spectrum; a large, bright nebulosity, too faint to be contributing to the nebular spectrum previously mentioned; if there are any changes in this large nebula, they are inconspicuous.[67] The conditions of excitation of the spectra of R Aquarii are even more complex and interesting than those for Z Andromedae.

CI Cygni.—The spectrum shows bright lines of H, HeI, HeII, NIII, [OIII], [FeII].[68] Several dark lines are seen. Merrill considers that the spectrum is in the same class as those of Z Andromedae and R Aquarii. Here we consider that CI Cygni is another double (or triple) object: a red star, a blue star, and a nebula (which may possibly be the outer envelope of the red star). The variation is irregular[69]; the light curve shows one pronounced maximum, not unlike those observed for Z Andromedae, and we may suppose that the blue star is responsible for it. No evidence is available concerning the variation of the red component. The star would repay intensive study.

[60] S. Gaposchkin, H.A., 105, No. 27, 1936.

[61] Joy, P.A.S.P., 39, 234, 1927.

[62] Pop. Astr., 31, 658, 1923; Publ. Dom. Ap. Obs., 4, 119, 1928.

[63] Mrs. Fleming, H.C. 168, 1911.

[64] Hogg, P.A.S.P., 44, 238, 1932.

[65] N. K. Greenstein, H.B. 906, 1937.

[66] Merrill, Mt. W. Contr. 514, 1935.

[67] Lampland, Pop. Astr., 30, 162, 1922.

[68] Merrill and Humason, P.A.S.P., 44, 56, 1932; Merrill, Humason, and Burwell, Mt. W. Contr. 456, 1932; *cf.* Miss Cannon, H.B. 778, 1922.

[69] Miss Cannon, H.B. 778, 1922; N. K. Greenstein, H.B. 906, 1937; *see* Graff, B. Z. No. 10, 1922; Parenago, N.N.V.S., 4, 276, 1934.

RW Hydrae.—The spectrum[70] shows bright lines of H, HeI, HeII, NIII, [OIII] (4363 only). The underlying absorption spectrum is variable between K5 and M2. The light curve is that of an abnormal long-period variable[71]; the range in particular is unusually small, less than a magnitude. The spectroscopic and photometric evidence makes it seem probable that the star is another double (or triple) system.

AX Persei.—Bright lines of H, HeI, HeII, NIII, [OIII], [NeIII] are superimposed on a spectrum of Class K0p, with titanium oxide bands corresponding in intensity to spectral class M3.[72] The light curve shows irregular changes of brightness similar to those shown by Z Andromedae.[73] Here again it seems probable that a double (or triple) system is involved.

The five systems just discussed all present similar phenomena and problems. For all of them there are three alternative pictures: a single object emitting all three observed spectra; two stars, of very different effective temperatures, the hotter exciting the nebular spectrum in the outer atmosphere of the cooler; and two stars involved in nebulosity, in which the hotter of the two excites a nebular spectrum. It would be irresponsible to pronounce in favor of any one of these three pictures at present. A careful spectrophotometric study would furnish the necessary basis of fact. A comparison of visual and photographic light curves for Z Andromedae indicates that the color differs greatly at different times, the star being bluest at the pronounced maxima; this qualitative evidence is in conflict with the first picture. Another significant fact is the high intensity of the auroral line 4363 of [OIII] in all the spectra named, relative to 4957 and 5007, the nebular lines arising from the same atom.[74] This excess of the auroral line over the nebular lines, while characteristic of early stages of the spectra of novae,[75] is comparatively rare in the spectra of galactic nebulae; I.C. 4997 is the most striking example,[76] but it should be noted that a majority of the brighter Magellanic nebulae have the auroral line the strongest.[77] The relative intensities of the [OIII] lines, coupled with the observation that the cooler components of the (hypothetical) pair are in all cases luminous red stars, presumably of very low density, makes the second alternative (two stars only) worth considering. The observational material necessary for deciding between the second alternative and the third should be provided by a comparison of the R Aquarii nebula and the nebulous object that gives the star its high-excitation, bright-line spectrum.

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[70] Merrill and Humason, P.A.S.P., 44, 56, 1932.

[71] Shapley and Yamamoto, H.B. 810, 1924.

[72] Merrill and Humason, P.A.S.P., 44, 56, 1932; Merrill, Humason, and Burwell, Mt. W. Contr. 456, 1932.

[73] Lindsay, H.B. 888, 1932.

[74] Merrill, Mt. W. Contr. 513, p. 22, 1935.

[75] See Boyce, Menzel, and Payne, Harv. Repr. 93, 1933.

[76] Wright, Lick Publ., 18, 247, 262, 1918.

[77] See H.A., 76, 19, 1916.

One star is known that combines the light curve of a long-period variable of small range and the bright-line spectrum of a star of relatively high excitation (H, HeII), containing no observed forbidden lines. The star is SY Muscae[78]; but the spectral observations are incomplete, and it is not improbable that if good spectra were obtained, SY Muscae might be found to share the other characteristics of the group of stars just mentioned.

Three more stars, with absorption spectra of late type, are known to show the forbidden lines of ionized iron; possibly they should be regarded as members of the preceding group.

W Cephei.—The spectrum, classed as Kp at Harvard, Mep at Mount Wilson, shows forbidden lines of ionized iron.[79] The variations are irregular.[80]

WY Geminorum.—The spectrum is of the same type as that of W Cephei.[81] The variations are irregular, and rather leisurely.[82]

WY Velorum.—The spectrum is of Class Map, and shows the forbidden lines of ionized iron.[83] The variation is very slow; there is a gradual rise in brightness, followed by a slow fall, both taking several years.

It must not be forgotten, in attempting to interpret these and other spectra, that forbidden lines of ionized iron have been photographed in the spectra of several apparently normal long-period variables at minimum.[84] Some long-period variables (such as R Aquarii, o Ceti) have (variable) blue companions; and we do not know how far they are exceptional. Thus the range of possible conditions available for the theoretical interpretation of the spectra is almost too wide.

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[78] N. K. Greenstein, H.B. 906, 1937.

[79] Adams and Joy, Pop. Astr., 30, 103, 1922; Humason, P.A.S.P., 34, 58, 1922; Merrill, Humason, and Burwell, Ap. J., 61, 397, 1925; *ib.*, 76, 169, 1932.

[80] Applegate, H.B. 764, 1922; see also Prager, G.u.L., II, 1, 266, 1934.

[81] Humason, P.A.S.P., 34, 133, 1922; Mt. W. Rep., 1922; Adams, Ap. J., 81, 220, 1935; Redman, M.N., 92, 118, 1932; Publ. Dom. Ap. Obs., 6, 34, 1931.

[82] Shapley, H.B. 767, 1922.

[83] Shapley, H.B. 782, 1923.

[84] Merrill, Mt. W. Contr. 399, 1930; Mt. W. Contr. 513, 1935.

The third group of stars mentioned on page 312 contains intrinsic variables with forbidden lines in their spectra. By excluding novae we remove with certainty the stars η Carinae[85] and RT Serpentis[86]; it is far from certain that AG Pegasi, Z Canis Majoris, and RX Puppis are not in fact more nearly novae than anything else. The star XX Ophiuchi is the only remaining object, and the four objects will now be briefly described.

Z Canis Majoris.—The variation is gradual, smooth, and quite without periodicity.[87] Merrill[88] states that the spectrum is rather like those of H.D. 45677 and H.D. 51480, but the bright lines tabulated in the description of the spectrum are all permitted lines.[89]

XX Ophiuchi.—The so-called "iron star," XX Ophiuchi is an irregular variable of small range.[90] The spectrum, classified as Bp (H.D. 161114) consists primarily of bright lines, but differs greatly at different times.[91] The light curve gives the impression of a star which, like R Coronae Borealis, has a normal brightness and becomes fainter at irregular intervals; XX Ophiuchi does not, however, share any other characteristic of the R Coronae Borealis class, and cannot be included in it. No star is known that resembles it in spectroscopic behavior; possibly such objects as X Persei and AE Arae may have similar variations of brightness.

AG Pegasi.—The peculiar, variable spectrum of AG Pegasi (+11°4673), basically of Class B, has been discussed by Merrill.[92] It presents a very complex velocity picture, the lines of different elements differing in their behavior. Merrill suggested a possible period of about 800 days for the variations of velocity. The star is variable in brightness,[93] in an apparently irregular manner. By collecting early observations, Lundmark[94] has derived a light curve that possibly has some similarities with that of P Cygni in 1600, though AG Pegasi has apparently had a smaller range. That the star is really very similar to P Cygni (*q.v.*) is not improbable; possibly after a couple of centuries the forbidden lines now seen in its spectrum, if the result of an outburst, will have disappeared.* The star has been briefly considered in the chapter on novae.

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[85] See p. 265.

[86] See p. 264.

[87] Miss Walker, H.C. 225, 1921; unpublished light curve kindly communicated to the writers; Beyer, Erg. A.N., 8C, 72, 1931.

[88] Mt. W. Contr. 334, 1927.

[89] Vorontsov-Velyaminov, New Stars and Galactic Nebulae, 271, 1935, states (apparently without foundation) that [FeII] lines are present.

[90] Miss Woods, H.C. 292, 1926.

[91] Merrill, Ap. J., 75, 137, 1926.

[92] Merrill, Mt. W. Contr. 381, 1929.

[93] H.B. 762, 1922.

[94] A.N., 213, 93, 1920.

RX Puppis.—The spectrum of RX Puppis (H.D. 69190) was first noticed as showing a similarity to that of η Carinae.[95] The spectrum shows bright lines of H, HeII, [OIII], [NeIII], the strongest line being the auroral line 4363 of [OIII].[96] Ludendorff[97] suggested that the star might be of R Coronae Borealis class, but neither light curve nor spectral observations substantiate this ascription. The variation of brightness is very slow, and at first a period of twenty years was suggested[98]; but no change of brightness was observed[99] between 1913 and 1924, and irregular, slow changes seem now to be indicated, probably similar to, though slower than, those of Z Canis Majoris and AG Pegasi.

The four objects just mentioned are difficult to classify. By extending the definition of a nova to any star that suffers a sudden outburst of brightness (accompanied by an outflow of matter), however small, we could include AG Pegasi certainly in that class, probably also Z Canis Majoris and RX Puppis. It would, however, be necessary to include also the majority of the Be stars; and such an expansion of the class of novae would serve no useful purpose. No doubt all these objects, like the Be stars (*q.v.*) are surrounded by envelopes of some kind; the envelope round AG Pegasi is very possibly of its own making; whereas XX Ophiuchi may well be a true obscuration variable, exciting a nebular spectrum in the matter that surrounds it. Thus we may have very similar spectra associated with different types of variation.

52. Irregular Variables Related to the Nebular Group.—

After the sorting and classification that have been done in the preceding chapters and section, there remain a few apparently irregular variables of Class G and earlier, and some, at least, of these appear to share the characteristics of the stars mentioned in the present chapter. They are enumerated in Table XI, IV.

The seven stars not incompletely observed, that definitely vary, can be brieflly described.

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* Possibly such bright lines may once have been present in the spectrum of P Cygni.

[95] H.C. 17, 1897.

[96] H.A., 93, 268, 1919.

[97] Handbuch d.Ap., 6, 77, 1928.

[98] H.C. 182, 1914.

[99] H.B. 809, 1924.

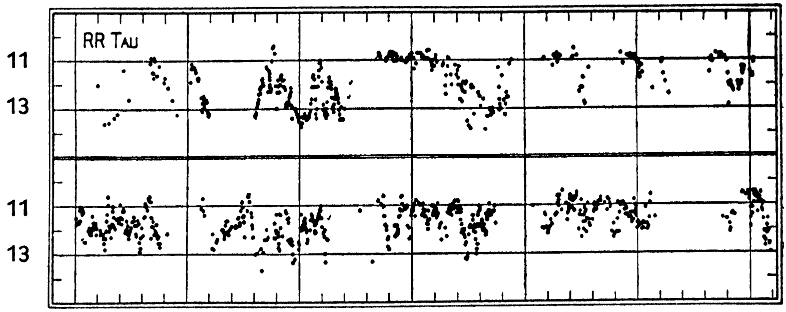

Figure XI, 2.—Observations of RR Tauri, (between J.D. 2425000 and 2431000) made by the A.A.V.S.O. and other groups of observers. The magnitudes were compiled by Mr. Campbell, and are used here with his kind permission.

TABLE XI, IV

IRREGULAR VARIABLES, CLASS G AND EARLIER

Star	Des.	Maximum	Amplitude	Spectrum	Remarks
		m	*m*		
RW Aur	050130	9.0	3.0	G0	See below.
UY Aur	044530	*11.6*	*2.4*	G0e	See below.
U Boo	144918	9.0	3.7	G	Irregular (Müller, A.N., 223, 281, 1924; Jacchia, Bologna Publ., 2, 225, 1933).
UV Boo	141826	7.4	1.2	F5	See below.
SV Cep	221973	9.4	0.6	A	Little known, apparently irregular.
NO Cyg	194637	*13.1*	*1.0*	G5	Very little known; see A.N., 249, 259, 1933.
TZ Her	163138	8.5	(1.0)	F5	More than one period has been assigned, but Lassovsky and Detré (A.N., 252, 197, 1934 and Gaposchkin, H.B. 903, 1936) conclude that the star does not vary, at least in the interval studied.
RZ Lac	223152	8.9	0.8	A0	See below.
X Per	034930	6.0	0.6	B0ne	See below.
RR Tau	053326	10.1	3.9	. .	See below.
UX Tau	042418	*10.5*	*2.9*	G5	See below.

RW Aurigae.—Parenago,[100] after collecting all available material, has reached the following conclusions: (i) the changes are large and rapid, the range being three to four magnitudes; and the star may change by a magnitude in a few hours; (ii) the star is yellow (color index = +0.68±0.06, spectrum Class G); (iii) the variation is similar to that of RR Tauri. Zinner[101] has also concluded that the variation is irregular, with rapid changes.

UY Aurigae.—First described as a very irregular Cepheid,[102] this star is now generally considered quite irregular.[103]

UV Bootis.—A regular period of $36^d.8$ was first suggested by Kopal,[104] but both he[105] and Rügemer[106] later concluded that the variation is irregular.

RZ Lacertae.—The star is irregular, with rapid variations within a day.[107] Merrill and Burwell give the spectrum as B9e (see Table XI, V).

X Persei.—The variations are apparently quite irregular, though a possible period has been suggested. The star would repay careful investigation, observations of brightness and spectrum being made concurrently. The changes of brightness seem to be rapid. The spectrum is of Class Be, and probably X Persei and AE Aurigae[108] are closely similar to one another.

RR Tauri.—The variations seems to be truly irregular, though Graff[109] considers that regularities do exist.

UX Tauri.—Incompatible periods were derived for this star by Parenago and Zessewitsch[110]; but more recently Rügemer has concluded from photographic observations that the star is irregular.[111]

Here we have a group of five yellow stars and two blue ones that vary in an apparently irregular manner. The former seem to resemble R Coronae Austrinae; the variations of the latter recall those of XX Ophiuchi. None of them is known to be associated with nebulosity; none is of directly known absolute magnitude. There is a possibility that all are Main-Sequence stars, caused to vary by invisible nebulosity—and for RR and UX Tauri this is rather more than a possibility, because of the extensive nebulosities that are known to exist in their neighborhood. If spectroscopically these stars were shown to be dwarfs, the probability that they are nebular variables would be increased. At the least, we need not consider that the existence of these irregular yellow variables is very mysterious. The important problem that they suggest is a close comparison between them and variables known to be in nebulosity, with a view to deciding how far they differ in all observable properties.

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[100] N.N.V.S., 4, 222, 1932.

[101] Astr. Abh., 4, No. 3, C7, 1922.

[102] Graff, B.Z., 6, 29, 1924.

[103] Koyama, Kyoto Bul. 222, 1931; Beyer, *see* G.u.L., II, 2, 110, 1936; Parenago, N.N.V.S., 4, 41, 1932.

[104] B.Z., No. 6, 1931.

[105] A.N., 248, 9, 1933.

[106] A.N., 255, 175, 1935.

[107] See G.u.L., II, 2, 174, 1936.

[108] Miss Boyd, H.B. 891, 1933: "spectrum may resemble novae or P Cygni class".

[109] B.Z. No. 14, 1922; see, however, Jacchia, A.N., 240, 121, 1930.

[110] Parenago, N.N.V.S., 4, 154, 1933; Zessewitsch, B.Z. No. 15, 1927.

[111] A.N., 255, 180, 1935.

53. The Spectrum Variables.—An important group of variable stars is that containing stars with variable atmospheres — the so-called spectrum variables, discovered from changes in their spectra. Such stars, of course, fall in many categories: eclipsing stars show spectral changes due to the presence of the spectra of two components changing in relative position; some few even show spectral changes as a presentation effect (a special aspect of reflection effect).[112] The spectroscopic binaries proper, such as β Aurigae, show evident spectral changes as a result of their orbital motion; but these stars we do not now discuss. The so-called spectroscopic binaries of which it is merely known that they show apparent changes in radial velocity are a more difficult case; some are of course spectroscopic binaries of undetermined period, but even a few of those that appear truly periodic (like ϕ Persei) may be true spectrum variables. Others, such as 27 Canis Majoris, are probably pure spectrum variables in the sense that the whole process of variation is an atmospheric phenomenon, the apparent changes of radial velocity being complicated (in some cases even caused) by changes in the intensity and structure of the bright lines. The largest and best known group of spectrum variables contains the Be stars; it is far easier to study than many other similar groups, because of the extensive and complete manner in which it has been catalogued by Merrill and Burwell. Their "Catalogue and Bibliography of Stars of Classes B and A whose Spectra have bright Hydrogen Lines"[113] has done for the Be stars what the "Geschichte und Literatur" has done for variable stars in general, and it renders unnecessary any extended bibliographic references in the present section.

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[112] See Bailey, H.C. 11, 1896; Miss Cannon, H.A., 28, 1907; Miss Maury, H.A., 84, 169, 1920; H.A., 84, 178, 1920; Struve and Ebbighausen, Ap. J., 80, 371, 1934.

[113] Mt. W. Contr. 471, 1933.

The list given by Merrill and Burwell contains 416 stars. "The spectra of many, possibly all, of the stars . . . are variable to a greater or less extent" as they state in the description to their table. In Table XI, V is given a selected list of galactic Be stars with known spectral variations. Merrill draws a distinction between Be stars proper (with one or two bright components, which may or may not be of equal intensity, superimposed centrally on a broad absorption line) and P Cygni stars (with a bright component to the red of an absorption line). The P Cygni stars are relegated to Table XI, VI.

Table XI, V contains six recognized variable stars (AB Aurigae, X Persei, R Monocerotis, RT Serpentis, β Lyrae, and RZ Lacertae). Of these, RT Serpentis is a true nova, and β Lyrae an eclipsing star; the others seem to be irregular variables. Probably Pleione and α Cygni are also slightly variable[114]; thus more than one third of the Be stars that are known to vary in spectrum vary also in brightness. Four of the fourteen stars tabulated as having bright iron lines are known variables.

A list of galactic P Cygni stars is given in Table XI, VI. Thirteen of these stars—over fifty per cent—have been found by ordinary methods to be variable, and apparently even the four eclipsing stars (GG Carinae,[115] −66°3307, β Lyrae, and RY Scuti) have irregular variations superimposed on the mean light curve. Six of the stars (all variable) have bright iron lines in their spectra. Probably many of the other stars in the table are undetected variables; Miss Hoffleit[116] found a high percentage of variability among galactic P Cygni stars.

While the variable stars of Table XI, V are fairly similar in general behavior, the variable P Cygni stars unite a large number of types of object. Here we find eclipsing stars; novae (η Carinae, P Cygni); white dwarfs (companions of o Ceti and, if postulated, of R Aquarii); slow irregular variables of large range (Z Canis Majoris, AG Carinae), rapid irregular variables

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[114] See pp. 306, 309.

[115] But see p. 304; it may not be an eclipsing star at all.

[116] H.B. 892, 1933.

Table XI, V
Selected List of Galactic Be Stars

Star	H.D.	R.A. (1900)		Dec.		MWC	Mag.	Spectrum	Remarks
		h	*m*	°	′				
γ Cas	108	0	0.9	+63	7	9	2.2	B0ne*	Spectrum variable. Light variable. Near nebula; see p. 305.
+62°259	9105	1	24.6	+62	51	13	7.5	B5s(e)	Spectrum variable.
φ Per	10516	1	37.4	+50	11	16	4.2	B0ne*	Spectrum variable. Velocity variable. Light variable.
+59°625	20134	3	9.1	+59	41	64	7.5	B2e	Spectrum variable. Light variable.‡
H.R. 985	20336	3	11.2	+65	17	65	4.8	B3e*	Spectrum variable.† P=1600 days; not binary.
ψ Per	22192	3	29.4	+47	51	69	4.3	B5ne*	Spectrum variable.
Electra	23302	3	39.0	+23	48	72	3.8	B5neα	Light constant‡; see p. 305.
Merope	10516	1	37.4	+50	11	16	4.2	B0ne	Light constant‡; see p. 305.
Alcyone	23630	3	41.5	+23	48	74	3.0	B5ne	Light constant; see p. 305.
Pleione	23862	3	43.3	+23	51	75	5.2	B8n(e)	Spectrum variable. Light variable; see p. 305.
X Per	24534	3	49.1	+30	45	78	6.0–6.6	Bone	Spectrum variable. Light variable; see p. 321.
c Per	25940	4	1.4	+47	27	81	4.0	B3ne	Light variable?‡ Velocity variable.
AB Aur	31293	4	49.4	+30	24	93	7.2–8.4	A0ep	Light variable. Spectrum variable.
11 Cam	32343	4	57.4	+58	50	96	5.3	B3e*	Spectrum variable.†
105 Tau	32991	5	2.0	+21	34	98	6.0	B3ne	Spectrum variable.

TABLE XI, V—*Continued*

Star	H.D.	R.A. (1900)		Dec.		MWC	Mag.	Spectrum	Remarks
		h	*m*	°	′				
+40°1196	33232	5	3.7	+40	53	100	8.1	B(3)e	Spectroscopic binary.[1]
25 Ori	35439	5	19.6	+ 1	45	110	4.7	B3ne*	Spectrum variable.†[2] Light variable?‡
120 Tau	36576	5	27.6	+18	29	111	5.5	B3ne	Spectrum variable.†
ζ Tau	37202	5	31.7	+21	5	115	3.0	B3e*	Spectrum variable†; period 430^d?
ω Ori	37490	5	33.9	+ 4	4	117	4.5	B3e	Spectrum variable. Velocity variable. Light variable?‡
−6°1391	41335	5	59.4	− 6	42	133	5.1	B2(n)e*	Spectrum variable.†
−11°1460	44458	6	16.8	−11	44	138	5.5	B2ne	Spectrum variable.
	41566					..		O	Spectrum variable.[3] Light variable.
β₁ Mon	45725					143	4.7	B3ne	Spectrum variable.†
β₂ Mon	45726	6	24.0	− 6	58	..		(Be)	Spectrum variable.†
β₃ Mon	45727					144	5.6	B3ne	Spectrum variable.†
+10°1172	259431	6	27.6	+10	24	147	9.0	B2e	
R Mon	.....	6	33.7	+ 8	49	151	9.3–14.0	Pec.*	See p. 304.
−6°1775	50138	6	46.7	− 6	51	158	6.6	B8e	
27 CMa	56014	7	10.2	−26	10	170	4.7	B5e	Spectrum variable. Velocity variable.
ω CMa	56139	7	10.7	−26	35	171	3.8	B3e*	Spectrum variable.
−16°1810	58343	7	20.1	−16	0	177	5.2	B3se	
J Vel	89890	10	17.2	−55	33	201	4.6	B5e	Spectrum variable.
ϰ Dra	109387	12	29.2	+70	20	222	3.9	B5e	
μ Cen	120324	13	43.6	−41	59	229	3.3	B3e*	Spectrum variable. Light variable?
η Cen	127972,3	14	29.2	−41	43	232	2.6	B3ne	Spectrum variable.

TABLE XI, V—*Continued*

Star	H.D.	R.A.	(1900)	Dec.		MWC	Mag.	Spectrum	Remarks
		h	*m*	°	′				
$\varkappa^1$ Aps	137387	15	20.6	−73	2	235	5.6	B5ne	Spectrum variable.
θ CrB	138749	15	28.9	+31	42	237	4.2	B5ne	
−13°4302	142983	15	52.6	−13	59	239	4.7	Apeα	
χ Oph	148184	16	21.2	−18	14	241	4.8	B3e*	Spectrum variable.†
−33°12319	160095	17	32.9	−33	29	263	8.7	B8e	
RT Ser	......	17	34.3	−11	53	265	9.2–[16	Pec	See p. 264.
−21°4779	163296	17	50.3	−21	56	275	6.6	A2e	
+19°3494	164447	17	56.1	+19	31	279	6.4	B9e	
+24°3395	168957	18	17.3	+25	1	292	6.9	B5e	
−14°5039	169454	18	19.6	−14	2	294	6.8	B0se	
β Lyr	174638,9	18	46.4	+33	15	306	3.4–4.3	Bep	Eclipsing star; see p. 86.
−19°5312	178175	19	2.4	−19	27	311	5.4	B3e	
υ Sgr	181615,6	19	16.0	−16	8	313	4.6	Ave	
b^{2}Cyg	191610	20	5.7	+36	33	329	4.8	B3ne	Spectrum variable.†
20 Vul	192044	20	7.8	+26	11	331	5.9	B8ne	
α Cyg	197345	20	38.0	+44	55	351	1.3	A2seα	Spectrum variable.[8] Light variable. Color variable; see p. 309.
λ Cyg	198183	20	43.5	+36	7	352	4.5	B6e	Spectrum variable.†
+46°3111	199478	20	52.4	+47	2	358	5.8	B8seα	
f^1 Cyg	200120	20	56.4	+47	8	359	4.9	B3ne	Spectrum variable.
60 Cyg	200310	20	57.6	+45	46	360	5.2	B3ne	Spectrum variable.
υ Cyg	202904	20	13.8	+34	29	364	4.4	B3ne	Light variable?‡
ε Cap	205637	21	31.5	−19	54	373	4.7	B5pe	Spectrum variable, peculiar.
+64°1607	208682	21	52.9	+64	52	381	5.8	B3ne	Spectrum variable.
25 Peg	210129	22	3.1	+21	13	385	5.7	B8ne	Spectrum variable.†

TABLE XI, V—*Continued*

Star	H.D.	R.A. (1900)		Dec.		MWC	Mag.	Spectrum	Remarks
		h	*m*	°	′				
31 Peg	212076	22	16.6	+11	42	387	4.9	B3e	Spectrum variable.†
π Aqr	212571	22	20.2	+0	52	388	4.6	B1ne*	Spectrum variable.† P=1087^d, not constant.
8 Lac	213088	22	31.4	+39	7	390	5.8	B3ne	Spectrum variable.
RZ Lac	214197	22	31.6	+52	14	391	8.9–9.7	B9e	Irregular variable.
+47°3985	217050	22	52.7	+48	9	394	5.2	B3ne	Spectrum variable.†
β Psc	217891	22	58.8	+ 3	17	396	4.6	B5e*	Spectrum variable.†
+49°4045	218393	23	2.6	+49	40	397	6.8	Ave	Spectrum variable.
+60°2636	223960	23	48.9	+60	18	403	7.0	A0seα	Spectrum variable.

* Bright lines of Fe II (Merrill, Mt. W. Contr. 334, 1927).

† McLaughlin, Pub. Univ. Obs., Michigan, 4, No. 13, 1932.

‡ Photoelectric observations; see Güssow and Guthnick, Kl. Veröff. Ber.-Bab., No. 8, 1930.

[1] Merrill, Mt. W. Cont. 491, 1934. A spectroscopic binary, period 3710 days, minimum mass 80⊙, probably a true binary.

[2] See the recent detailed study by Miss Dodgson, Ap.J., 84, 180, 1936.

[3] C. A. Rieke, H.B. 891, 1933; one of the very few known variable O stars.

[4] Cleminshaw, Ap.J., 83, 487, 1936; period 10 years?

[5] See p. 309.

of small range (XX Ophiuchi). The P Cygni type of spectrum is not the mark of one sort of object or condition; and here we should emphasize the danger of treating any group with spectral peculiarities, and particularly this one, as though it were homogeneous.*

General properties of Be stars are not very dissimilar to those of normal stars of the same spectral classes. Merrill's tabulation of the data concerning the four hundred and sixteen stars on his list shows that the ratio of Be stars to the total number of stars in the class falls from its maximum value in Classes B0 to B3, to a very small percentage in Classes A2, A3, and A4. He also shows that the Be stars are even more "gregarious" than the normal B stars, and notes the additional significant fact that they adhere more closely to the galactic circle, and are less affected by the Local System, than the B stars in general. This he attributes to a possible difference in brightness between the groups of stars, regarding the Be stars as perhaps a magnitude brighter.[117] Gerasimovič[118] had previously derived an even greater excess (—2) of luminosity for the Be stars, but subsequent work has tended to reduce his estimate. McLeod[119] concluded that the difference was not greater than $0^m.4$; and Gerasimovič,[120] after a critical rediscussion of the data, derived the value $-1^m.5$ for the difference (M_{Be}—M_B). Mineur,[121] however, obtains the reasonable result that the Be stars are ordinary giants, with no difference in average absolute magnitude; he ascribes the emission (in common with most other authors) to the existence of an extensive atmosphere.

It is not within the scope of this book to discuss the extensive theoretical work that has recently been done concerning the Be stars; but it seems to be relevant to outline some of the problems

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* We note that Table XI, VI shows two pairs of stars (GG and AG Carinae and RY Scuti and —12°5034), that are very close together in the sky, possibly also in space. Possibly there is here a suggestion that the spectral similarity springs from a combination of environment and a star of suitable exciting power, so that the P Cygni character is, at least in some cases, a matter of the interaction of a star with nebulosity.

[117] Merrill and Burwell, Mt. W. Contr. 471, 1933.

[118] H.B. 849, 1927.

[119] H.B. 894, 1934.

[120] H.B. 897, 1934.

[121] C.R., 200, 2145, 1935.

Table XI, VI
Selected List of Galactic P Cygni Stars†

Star	H.D.	R.A. (1900)		Dec.		MWC	Mag.	Spectrum	Remarks
		h	*m*	°	′				
o Cet (comp.)	.....	2	14.3	− 3	26	35	10 (var)	Bep*	Light variable; p. 124.
−12°1500	45677	6	23.7	−13	0	142	*7.5*	Bep	
AX Mon	45910	6	25.2	+ 5	57	145	*6.7–6.9*	Beq	Spectrum variable. Velocity variable; must be a binary.
−10°1774	51480	6	52.4	−10	41	161	7.0	B8eq	
......	51585	6	52.8	+16	28	162	..	Beq?	
Z CMa	53179	6	59.0	−11	24	165	8.4–11.5	Beq*	Spectrum variable. Velocity variable; see p. 318.
η Car	93308	10	41.2	−59	10	214	−0.6– *7.9*	Pec.*	Spectrum variable, peculiar nova; see p. 265.
GG Car	94878	10	52.0	−59	52	215	*9.5–10.0*	Beq	Eclipsing star?; see p. 304.
AG Car	94910	10	52.2	−59	55	216	*6.5– 8.0*	Beq	Irregular variable; see p. 303.
−71°1889	138403	15	26.9	−71	34	236	*9.0*	Beq	
−65°3171	141969	15	46.7	−65	52	238	*9.2*	Beq	
......	151895	16	45.1	−64	4	242	*12.5*	Beq	
ζ¹ Sco	152236	16	47.0	−42	12	243	4.9	B1seq	Spectrum variable.
AE Ara	......	17	33.6	−47	0	..	*11.6–13.8*	Beq?	See p. 311.
−46°11816	161044	17	38.2	−46	3	267	11.0	Beq	
XX Oph	161114	17	38.6	− 6	14	269	*9.6–10.9*	Pec.*	Spectrum variable. Velocity variable; see p. 318.
−27°11944	......	17	41.9	−27	59	272	9.0	Beq	
−66°3307	......	18	10.4	−66	7	...	*9.0–11.0*	Beq	Eclipsing star; see p. 89.
−12°5034	169226	18	18.6	−12	15	293	9.1	Be(q)	
RY Sct	169515	18	19.9	−12	45	295		Pec.	Eclipsing star; see p. 88.
P Cyg	193237	20	14.1	+37	43	338	*3–[6*	B1eq	Spectrum variable; see p. 266.
+47°3487	......	20	27.2	+43	59	374	9.1	B3eq	
AG Peg	207757	21	46.2	+12	9	379	*6.3–7.7*	Bep*	Spectrum variable.
VV Cep (comp.)	208816	21	53.8	+63	9	...	7.4	Be	Velocity variable; see p. 86.
R Aqr (comp.)	......	23	38.6	−15	50	400	9(var)	Pec.*	Spectrum variable. Light variable; see p. 123.

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† Including stars at times resembling P Cygni, and related peculiar stars.
* Bright lines of FeII.

that involve jointly the Be stars as objects with peculiar spectra, and as variable stars.

The features of the (intrinsic) spectrum variables that are important from the standpoint of interpretation are: (i) variations of relative intensity of the red and violet components of the bright lines, and of the total intensity of the bright components; (ii) variations in radial velocity; (iii) variations in brightness of the star as a whole, and also of its color. Of these features, (i) and (ii) are usually correlated,* and in some, though not in all cases, show rough periodicities of the order of ten years. It is probable that process (iii), when observed, is also related to (i) and (ii).

The most promising feature of the Be stars from which to begin an attack on the geometry of the systems is the profile and variation of the bright lines. Attempted interpretations have usually considered either rotating or expanding envelopes, the former being either equatorial rings or shells. The rotating ring hypothesis has been developed by Struve,[122] who showed that it was possible with a rotating ring to predict broadened profiles with intensity maxima at their edges. There are a number of objections to the formal hypothesis of rotating rings; from the standpoint of interpreting the data now in hand we note that it cannot easily account for changes in total brightness, nor in relative brightness of the components of bright lines. A more indefinite difficulty is that the rotational velocities are very great (of the order of 300 km/sec at the surface of the star), whereas the periodicities in the bright-line phenomena, when they are present, are of the order of a thousand days. With a star rotating on its axis in a period of the order of a day (as predicted from the broadened profiles of the absorption lines) it is difficult to see how relative intensities of the components of bright lines, which depend on an axis oriented in space, could remain constant over periods of the order of years.

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* The extent to which (i) may obscure or even simulate (ii) is a matter that should be, and never has been, critically examined. Not only for Be stars, but also for novae, it is a question of great importance. For a solution of the problem a careful spectrophotometric and theoretical study is needed.

[122] Ap. J., 73, 94, 1931; Struve and Swings, Ap. J., 75, 161, 1932.

An alternative theory, proposed by Gerasimovič,[123] appears more promising[124] in covering the observed facts; he examines the consequences of an expansion of an envelope that is repelled from the star under radiation pressure, as suggested earlier by Johnson.[125] The details of the theory would be out of place; but its main features appear to fit the facts better than any other that has yet been proposed. The variability of the Be stars, and the association of some of them with spectral features indicating nebulous surroundings, suggest that changes in the intensities of the bright lines may be produced by the passage of a star from a region of greater to a region of lesser density, the ratio of the intensity of red to violet component being a function of density gradient, and the separation of the components (as in the original form of the theory) being provided by the repulsion of the surrounding gas by radiation pressure. The quantity of matter required is very small—too small in most cases to produce noticeable nebulosity to any great angular distance.

Very hot stars will repel nearby nebular material, thus minimizing a pure obscuring effect; cooler stars will be less potent, and obscuring effects accordingly greater. The hottest stars in nebulous regions (Orion, Corona Austrina) do seem to be the least variable, while the cooler stars, comparable in temperature and brightness with the sun, vary more appreciably.

The possible association of Be stars with very diffuse nebulosity is in harmony with their gregarious tendency,* and with their closer adherence to the galactic plane (where nebulosity is most frequent—it is definitely less frequent in the plane of the Local System) than the B stars proper. Of the twelve regions where Merrill and Burwell mention the clustering the Be stars, seven are largely associated with nebulosity.

The present chapter actually covers a subject as extensive as, and largely distinct from, the rest of the book. Earlier chapters consider variable *stars*; here (save for the pure obscuration variables, which, if there really are any such, should be classed as eclipsed systems) we deal with variable *atmospheres*. All true variable stars have variable atmospheres, but a variable atmosphere is probably the property of all stars, whether obviously variable in brightness or not (as witness the solar envelope). In the present chapter we consider not only the atmosphere proper (to be defined, perhaps, in terms of gravitational subservience to the star), but also the more extended stellar envelopes, which may (novae) or may not (the Pleiades) have originally been part of the star they surround.

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[123] M.N., 94, 737, 1934.

[124] Rosseland, Theoretical Astrophysics, 291, 1936.

[125] M.N., 85, 813, 1925; *ib.*, 86, 300, 1926.

* The region of the double cluster in Perseus is well known as a hotbed of variable stars; and in the words of Merrill and Burwell: "the general stellar density [in the region] is scarcely equal to the average for the galaxy". This suggested slight deficiency may possibly be an effect of absorption, and an indication of the presence of nebulosity.

The problems that concern the nebular and spectrum variables are complex, and with a different sort of complexity from that of the intrinsic variables (the Great Sequence and the cataclysmic stars). They can be solved only by concurrent spectrophotometry and precise measurements of brightness, coupled with that knowledge of the factual basis and physical condition of nebular matter, which should be one of the first concerns of the present generation of astrophysicists.

F

ON TECHNIQUE

CHAPTER XII

DISCOVERY AND PHOTOGRAPHIC OBSERVATION OF VARIABLES

For at the first she will walk with him by crooked ways, and bring fear and dread upon him, and torment him with her discipline . . . . Then will she return the straight way unto him . . . . and show him her secrets. But if he go wrong, she will forsake him, and give him over to his own ruin.

Ecclesiasticus, iv.

The discovery of a variable star by its change of brightness depends on the amount and speed of the change, and on how often it occurs. Other things being equal, it is obvious that regular slow changes of large amplitude, and periods of several months, will be the most easy to detect. Stars showing such changes (long period variables) will therefore be the most completely represented in the lists of known variable stars.

54. Technique of Discovery.—i. *Visual Discovery.*—The first variable stars to be discovered were found accidentally because they were bright and had large ranges; therefore they comprised novae (such as Tycho's Nova of 1572), long period variables (such as Mira Ceti, discovered in 1596 by Fabricius, and χ Cygni), and eclipsing stars (such as Algol, known since 1667, but probably recognized as variable by the Arabs, many centuries earlier). At present the visual discovery of variable stars is confined to bright novae, and to stars accidentally noted as variable in sequences used for visual observing, or in studying comets and asteroids.* The visual discovery of variable stars can scarcely be said today to boast a technique. Historically speaking, most visual discoveries were more or less accidental (or incidental) and were confined to the brighter stars. Obviously visual discovery involves an accurate and detailed knowledge of the sky, which is only acquired with long and patient study.

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* Unconscious visual discovery of a variable star might be said to occur when a star, recorded in one of the visual Durchmusterungs, is now not to be found; or when a star now above the catalogue limit is missing from the Durchmusterung. The star S Centauri is probably a variable in the latter category.

ii. *Photographic Discovery.*—It was photography that gave life to variable star astronomy. There are three main methods of discovering variable stars photographically. First, systematic series of short equal exposures may be made on one photographic plate (method of multiple exposure). Secondly, photographs taken at different times with similar exposures may be compared. Thirdly, a negative may be compared with a positive made from another photograph of the same region taken with the same instrument at a different time. This third method, a variant of the second, has been found on the whole to permit of greater refinement and to lead to a greater number of discoveries, in proportion to the labor expended, than the comparison of two negatives. Probably the superior results from the positive-negative method arise from the fact that with it one observes the *sum* of the deviations of the two images of the variable from the mean, whereas by comparing two negatives one estimates only their *difference.*

All three methods of photographic discovery derive their power from the fact that the plate records many stars at once and under identical conditions, so that photographic effects irrelevant to the variation may be eliminated.

The method of multiple exposures was much used at the outset of the photographic study of variables. It can be (and has successfully been) rendered automatic, and the technique is capable of considerable elasticity and refinement. It is, however, applicable only to stars with periods shorter than a day (such as the cluster type stars) or whose variation is so rapid as to be sensible within an hour or two (such as eclipsing stars, R Coronae stars, and novae).

As a tool for discovering cluster type stars the method of multiple exposures is not particularly superior to the second and third photographic methods, except for stars of very short period—of the order of an hour. Such stars are uncommon, according to our present information; the most extreme is CY

Aquarii, a star with a period of 89 minutes. A systematic search for cluster type variables of such short period would present great difficulties and would in itself probably not justify the labor expended.

For the photographic discovery of a variable star, the exposures must be short compared with its period, or the variation will be averaged away, and this puts a limit on the brightness of the short-period stars that can be thus discovered. The fainter the star, the more powerful the instrument required for discovering its variability, and hence, in general, the larger the scale of the plate and the smaller the field. Thus it seems that a systematic survey for cluster type variables of very short period would be unfruitful; if one were made, speed and field being the chief requirements, the instrument of widest angle and largest available aperture should be used. Probably for profitable work an instrument would have to be specially designed.

An instrument such as that just suggested would be of little value in the discovery of R Coronae Borealis stars or novae, which are as readily discovered by the other methods, since most of those known remain bright or faint longer than a day. But there is a possibility of thus discovering very rapid novae, of whose existence there seems to be some slight evidence. The "peculiar object" noted by Hertzsprung[1] on one Harvard plate may have been a nova of this kind, although the varying appearance of the image suggested more strongly a member of the solar system.

The greatest value of a fast survey instrument for finding variable stars by multiple exposures would of course lie in the possibility of discovering eclipsing stars with minima very short compared to the length of their periods. If such an investigation were carried out, the plates should be borne in mind as a possible source of valuable information about cluster type stars of very short period.

The method of multiple exposure is of course invaluable for the *study* (as distinct from the discovery) of rapidly varying stars, of cluster, R Coronae, nova, and eclipsing type. But in this case it can be used with an instrument of great power and small field, as the position of the object is known, and the larger area needed in a survey is therefore not required.

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[1] H.B. 847, 1927.

The comparison of exposures made at different times remains the chief photographic method of discovering variable stars. By choosing the intervals and exposure times appropriately it is possible to provide for the discovery of a maximum number of variables of a given kind. The problems involved in this choice are surveyed in a later section.

iii. *Photoelectric Discoveries.*—The photoelectric cell, superior to the photographic plate in its ability to distinguish smaller differences of brightness (down to $0^m.01$) has not at present been able to reach faint magnitudes. However, with the development of methods of amplification and the use of powerful light collectors, a great increase in reach may be expected.

There are two main methods of photoelectric discovery of variable stars. The cell may be used in systematic surveys of small groups of adjacent bright stars. A larger field for photoelectric "discovery" in the past has been presented by spectroscopic binaries, and other stars with variable radial velocities; the former stand a good chance of being eclipsing stars of small range. These photoelectric eclipsing stars are fairly numerous.

Like the multiple exposure method, the photoelectric method has large applications in the study of known variables, and will indeed provide the ultimate data on the details of the light variation of variables bright enough to be studied in that way.

iv. *Design of a Photographic Discovery Program.*—The problem depends upon the desires of the investigator and upon the facilities at his command. We assume that he wishes to discover variable stars in order to understand them as well as possible, and thus that he desires to discover as completely as possible a maximum number of every type. (If he wishes to discover stars for distance determination the problem is quite different; in this case he will desire chiefly cluster type stars, and will accordingly work with one-or-two day runs scattered over a year or two).

v. *Stars Likely to be Variable.*—There are a number of groups of stars which are likely to be found to vary in brightness. True spectroscopic binaries, when examined photoelectric-

SUGGESTIONS FOR TYPES OF OBSERVATION REQUIRED

Type of Star	Observations
Cluster	One-or-two-day runs, fairly short exposures, over a period of two or three years, at intervals of a month or more.
Cepheid	Day intervals for a week or two, over an interval of two or three years.
Semi-regular	Continuous work at day intervals.*
Long period	Weekly or monthly observations for ten or twenty years.†
Irregular	Day intervals for a week or two, for two or three years.†
R Coronae	Continuous work at day intervals, except during fall to minimum.*
Novae	Continuous work at hourly intervals for the first month or two; then daily.*
SS Cygni stars	Continuous work at daily intervals, more often when brightening.*
Eclipsing	One-two-three-day runs, fairly short exposures, over a period of two or three years, at intervals of a month or more.*

Stars marked * would be better observed when discovered and their nature known, if put in the hands of visual observers who could work continuously.

Stars marked † should be studied further, with plates from the Harvard plate collection, for example. It is not in general worth while discovering such stars much beyond the thirteenth magnitude, for individual study.

ally, will often appear as eclipsing stars of small amplitude. Apparent spectroscopic binaries—stars with periodic variation of radial velocity, not referable to a physically possible orbital motion—will often appear as Cepheids or stars like RU Camelopardalis. And stars with variable but non-periodic radial velocities are apt to be irregular variables of small range.

Variations of spectrum may lead to the discovery of a variable star. All stars with variable spectra are worth examining for variability of light; β Doradus and ϕ Persei are examples of variables discovered in this way.

Stars of certain spectral classes are nearly certain to be variable. M stars with bright lines are almost (but not quite) without exception long period variables, and many have been discovered first from their spectra. Most stars of Classes N and R are variable; the former usually irregular, the latter somewhat addicted, though not confined, to R Coronae Borealis type. All stars with bright line spectra are likely to be variable, and some, like the "peculiar" stars spectrally resembling η Carinae, are among the most fascinating of variables.

The globular clusters are well known to be likely sites for variable stars, especially of the cluster type, and the Milky Way regions are of course more fruitful for variable star surveys than the regions of high galactic latitude, though the results from the latter have even more important bearings on galactic structure. Regions containing dark and bright nebulosity are especially important to search for variable stars, not because the number found is likely to be great, but because of the exceptional interest of any stars that may be discovered in a nebula.

55. Observation of Variables.—The study of a newly-discovered variable must usually begin with the measurement of its changes in brightness—the formation of a light curve. It is desirable to decide how accurately this is worth doing; accurate measurement is not itself a virtue, and there are cases where it is quite unnecessary. The development of an accurate technique is no substitute for thought about a problem. Too often is this forgotten with variable stars. An accurate light curve is fairly easy to form, but it is not therefore significant.

The things that can be observed about a light curve are: (a) shape, (b) amplitude, (c) mean magnitude, and, of course, any changes that may take place in any or all of these. A complete determination of all three gives what may be described as an accurate light curve.

Probably such a light curve is only necessary (in our present state of knowledge) for eclipsing stars, for which there is a reasonably precise theory of changes in brightness. The shape and amplitude for variables of the Great Sequence have rather vague statistical significance, but there is no precise theory connecting them with anything else. They are probably worth determining for such stars with reasonable accuracy, the amplitude within $0^m.20$. For all late type variables (irregular, semi-regular, and long period) shape and amplitude are probably unimportant except in the broadest sense.

Mean brightness is probably the most important datum for the light curve of a variable belonging to the Great Sequence, especially if one is interested in the star's distance as an individual, or as a member of a recognized group. This is because the absolute magnitude of intrinsic variables of known period is determinate within $\pm 0^m.2$ from the period-luminosity curve.

It is usual to express the period-luminosity relation in terms of *median* rather than mean magnitude, (average of maximum and minimum) largely for practical reasons. In the use of this empirical relation for the determination of the distances of isolated systems of stars, the fixity of median magnitudes of cluster type stars has been particularly useful, because if a star is known to be a cluster type variable it is not necessary to know the period accurately in order to proceed to a parallax—the median magnitude suffices. This median magnitude is to be determined by simply taking the average of the available estimates of brightness; supposing the phases of these to be distributed at random, the resulting mean must be the median magnitude.* A similar expedient has been used with spectral observations of Cepheids.

In determining the distance of a system by means of cluster type stars it is only necessary to be sure that the variables discovered belong to this type. When the stars considered are actually in globular clusters, the close resemblance between one cluster and another in all other measurable features leaves little doubt that the numerous variables in them are also similar. The consistency of the results obtained on this assumption with those obtained in other ways provides *ex post facto* justification for the identification. But in galactic regions, where the range of possibilities is larger, it is desirable to have independent evidence that the stars used for the determination of distance are cluster type variables. For an individual star, a determination of period cannot be dispensed with, but if measures of color show that an object or, more particularly, a group of objects, is blue, the probability is that an assumption of cluster type is justified.

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* This procedure is of course only valid if the whole range of the variable is covered by the observations. Median magnitude is only equal to mean magnitude for type c cluster variables, being numerically slightly greater (or fainter) for types a and b. (See Section 32.) Thus while median magnitudes of cluster type variables of all periods are the same, mean magnitudes must be a trifle fainter for the longer periods, since the type of variable is correlated with the length of period.

Thus for some purposes it is only necessary (as in this extreme case) to measure the average brightness without determining a light curve at all. For other studies it may be valuable to determine form and amplitude accurately, leaving the zero point of the light curve arbitrary. No rule can be laid down; the requirements of individual studies dictate the treatment.

Changes in form, amplitude, and mean brightness can be far more important than the quantities themselves, for example, for RV Tauri and SX Centauri stars. Happily, also, they can be more easily determined, as they call for differential rather than absolute work.

We shall, however, assume that the highest attainable accuracy is required in the light curve, and shall now survey the methods and standards of photographic photometry.

56. On Photographic Photometry as Applied to Variable Stars.—The photographic determination of the brightness of stars is a difficult matter. The photographic plate in itself is a source of many uncertainties. The qualities of the photographic emulsion are very far from stable. Not only may different batches of the same emulsion differ, sometimes considerably, in sensitiveness, and in relative sensitiveness to different colors, but also a given emulsion varies considerably in both these respects with age, temperature, and humidity. Thus photographic plates taken with the same instrument of the same object will differ, for photographic reasons only, by factors depending on the order and length of the exposures, on temperature and humidity during exposures, on temperature and duration of development and strength of developer, on detailed conditions of development, on length of time elapsed between exposure and development, and between manufacture and exposure, and on conditions, especially of temperature and humidity, to which the plate has been exposed in these intervals. Thus most photographic photometry is best done differentially, with an attempt to keep similar some of the effects just mentioned; for instance by making the comparisons on plates of the same emulsion and of the same age, kept together, exposed as nearly simultaneously as possible, and developed together; or perhaps better, by successive exposures on the same plate. The latter method introduces errors depending on order of exposure, but these can be eliminated by taking two successive plates, with the exposures in different orders.

When photographic differences have been eliminated there still remain differences depending on the optical qualities of the instrument used in making the photograph. The chief instrumental effects upon focal images arise from spherical and chromatic aberrations of the lens system used, distortion of the field, vignetting, and absorption in the optical system. These causes, which we need not discuss from the theoretical side, lead in practice to three types of error: those depending on the color of the star, on its brightness, and on its position in the field. All refracting telescopes give a combination of the three types of error; in reflectors we have only to reckon with the last two. We shall discuss each briefly.

i. *Color Equation.*—The difference between photographic magnitudes determined with different refractors, depending on the color of the star, are chiefly effects of differences in focal length for light of different wave lengths, and also to some extent of the absorption of light in the lens system. The latter, except for special systems, is numerically a small factor, though for some ultra-violet lenses, such as the one used in the two Yerkes Actinometries, it may be important. The difference of focal length is a serious factor, because it produces effects that inevitably have a magnitude equation; and because it is very sensitive to changes of focus. A photographic objective cannot be so made as to focus accurately light of all colors at once; most photographic objectives are designed to give good focus at two wave-lengths, and the parts of the spectrum between and on either side of these will be more or less out of focus, when the instrument is focused for them. The actual image of the star is therefore the superposition of a number of out-of-focus images of different sizes. This image pattern has been exploited by Tikhoff in his so-called "longitudinal spectrograph."

It is a source of serious systematic error, to photographic photometry, more important for large than for small focal lengths.

As an example of the large differences that the type of correction of a lens may introduce, we refer to an unpublished determination of the color coefficients of the 16-inch Metcalf refractor of the Harvard Observatory and the 10-inch Metcalf refractor for focal images. With the former instrument the magnitudes of the bright red stars appear too bright, and those of faint red stars appear too faint, when compared with the International Scale; with the latter instrument bright red stars appear too faint, faint red stars too bright. Faint red stars may show a difference of half a magnitude when results from the two instruments are compared.

On further examination the color coefficient is seen to be a function of the intensity of the image, not of the intensity of the light. It is the same, with one instrument, for focal images of the same strength, provided the focus has not been altered. For the 16-inch telescope, the redder portion of the photographic light (the blue-green on an ordinary plate) forms an out-of-focus image, which produces a considerable disc for bright stars, but does not affect the plate for faint stars; hence the bright red stars appear with exaggerated intensiy. For the 10-inch telescope, it is the ultraviolet light that forms the most intense out-of-focus image, and therefore the bright blue stars are accentuated, the faint blue stars relatively weaker. The difference between the two instruments lies partly in the correction of the lens, partly in the relative transmission of blue-green and the ultra-violet light.

It should theoretically be possible to determine a color correction for any one instrument, depending on the color and brightness of the star, and on the exposure time; in practice the problem is complicated not only by the photographic difficulties previously mentioned, but by the extreme sensitiveness of the color equation to focus. In general, the focus differs slightly, for example, with the temperature—enough with an instrument of long focus to cause an appreciable seasonal effect in the color equation, if a fixed focus is maintained.

It is best, if possible, to confine oneself to one optical system, when great accuracy (i.e., maximum freedom from accidental error) is desired. When it is necessary to pass from one optical system (and therefore from one system of magnitudes) to another, it is usual to express the difference in the form:

$$M_i - M_j = a + bM_i + cI_i$$

where M_i, M_j are the magnitudes in the two systems considered, and I_i is the color index in one of them. The coefficients a, b, and c, represent the differences in zero point (i.e., the constant difference between the systems), in scale, and in color equation. It is with the last of these that we are now explicitly concerned, but enough has been said to show that c is intimately bound up with b. The formula likewise assumes that the color equation is a linear function of the color (since it assumes a constant value for c), but this is neither theoretically probable, nor usually found to be so in practice. It is preferable to determine c as a function of I_i where systematic accuracy is of great moment. The practical determination of color equation is described in Subsection ix.

ii. *Magnitude Equation.*—The difference between plates made with different instruments, depending on the magnitude of the star, is always involved both with the color coefficient and with the distance correction. The dependence on color was described in the previous paragraph. The latter is fundamentally of the same nature. That part of the distance correction that is connected with the departure of the field from flatness results in the images near to the edge of the plate being slightly out of focus. Therefore the bright stars will give large images of exaggerated brightness, and the faint ones, which would impress the plate if their light were concentrated in a focal image, will fail to do so when it is spread over an area. Therefore magnitude scale will be exaggerated near the edge of the plate, and thus a definite magnitude equation is introduced for all stars not at the plate center.

iii. *Distance Correction.*—The effect of distance from the (optical) center of the plate—which should of course coincide with the actual center, but often does not—appears partly in the magnitude equation mentioned in the last paragraph. The size of this effect depends on the flatness of the field, and on the focal length of the telescope. Usually it is the most important distance effect, but sometimes the effect of vignetting is also considerable for lenses of wide angle. As with color coefficient and magnitude equation, these distance corrections make absolute fundamental magnitude work very difficult, and encourage adherence to one instrument, and to one position on the plate and a standard exposure, if great accuracy is desired.

iv. *Out-of-focus Photometry.*—The best way of eliminating the more serious color coefficients and magnitude equations — those depending on differences of focus, and on the brightness of the out-of-focus image—may be attained by working out of focus and then measuring the central portion of the out-of-focus image with a suitable photometer. The image itself may be simply set out of focus, or produced with the Schraffierkasette. The reason for the elimination of the errors that depend on focus and magnitude is obvious; the errors not thus eliminated are those produced by the absorption of the lens system and the effect of vignetting. The former is usually small compared with the others; the latter may easily be allowed for empirically, but its effect on the surface intensity of an out-of-focus image is usually small when compared with its effect on focal images.

v. *Atmospheric Extinction.*—In addition to the peculiarities of the photographic film and the characteristics of the photographic camera, the transmitting atmosphere has serious effects. Besides those differences of atmospheric transparency in different parts of the sky, which make comparison with distant standards so difficult, there are less recognized effects upon stars photographed simultaneously. The transmission of the atmosphere is more variable in the violet than in the blue and green, and many of the erratic variations noted for very blue stars on different nights are probably due to this cause. Some of these blue stars may be variable, but an observation that they are apt to be faint on nights of poor quality suggests that the atmosphere is often responsible. Thus there is reason in the suggestion that blue stars should be avoided as standards whenever possible, because of their erratic brightness on photographic plates (except, of course, when a star of similar color is to be estimated); red stars are to be avoided (except under similar circumstances) because of their large color coefficient in many magnitude systems, though if observations are confined to one instrument they may not be so undesirable for standards as very blue stars.

vi. *Magnitude Systems.*—What has been said above under the heading "photographic photometry" applies to all determinations of brightness made on photographic plates.[2] Hitherto the greater part of photographic photometry has been carried out for the spectral region in which the plate is most sensitive for stellar work*—that between 4000 and 4900 Angstroms. In particular, magnitudes determined by focal work on ordinary (unsensitized) photographic plates have come to be called "photographic" magnitudes; strictly speaking there is an infinite number of possible magnitude systems of this kind, determined by the qualities of instrument and plate. The magnitude system next in importance to the photographic is the so-called photovisual system, obtained by using a plate appropriately sensitized, combined with a yellow filter of appropriate transmission, to isolate a section of the spectrum of effective wave length about 5300 A, and about 200 A in width. This effective wave length is near to that of the accepted visual system, so that photovisual magnitudes are similar to visual magnitudes in a general way.

The number of possible magnitude systems is evidently governed only by the range of sensitizers and filters. The more monochromatic is the light used (in other words, the smaller the range of wave length transmitted by the filter and effective on the plate) the more consistent will the magnitude system be.† For the "photographic" system, which uses a range of a thousand Angstrom units, the effective wave length of the system is actually dependent on the position of maximum intensity in the stellar spectrum. This is one reason why the photographic system cannot be converted to other systems as easily as they can be interconverted; a more serious reason is the effect, on the zero point and scale of the photographic system, of the absorption associated with the Balmer series of hydrogen at Classes A and F.

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[2] See Seares, Science, 87, January, 1938, for the discussion of the general nature and problem of magnitudes, as determined by photographic methods.

* Not, of course, the most sensitive region of the plate itself, which lies further to the violet, but the region most strongly affected by the actual stellar energy transmitted by atmosphere and instrument.

† For example, a photographic Purkinje effect could not arise in purely monochromatic photometry.

A magnitude system is more consistent if it embraces a small range of wave length, because the range of focus is then small, and the color coefficients and distance corrections arising from this range of focus in refractors are therefore minimized. A small range of wave length can only be obtained by sacrificing the remainder of the starlight and the other spectral regions accessible on the plate, and this places restrictions on the brightness of the stars that can be studied. Photographic magnitudes are at present attainable for stars of the twenty-first magnitude; photovisual magnitudes for those of the sixteenth; and for other effective wave lengths the brightness is even more restricted. At present, therefore, the limited sensitiveness of the photographic plate makes it difficult to study the majority of variable stars in any but blue light.

vii. *Heterochromatic Standards.*—If work is extended to other effective wave lengths than those in the photographic and photovisual systems, standards must be set up in those wave lengths. At present the chief heterochromatic standard is in the Pleiades; but others can readily be set up by those who desire to carry on precise work in specified wave lengths. It is in fact almost essential that such standards should be set up with the actual combination of plate, filter, and instrument that is to be used in the investigation itself. In this fashion the red standards at the North Pole were established recently at Harvard.

viii. *Accuracy of Photographic Methods.*—The mean error of one photographic magnitude estimated by an experienced measurer from four good plates, by direct comparison with a standard (such as the North Pole) is about $\pm 0^m.06$. This error represents the joint contribution of the photographic emulsion, the instrument, the atmosphere, and the measurer. The results from focal plates are not appreciably improved by using a photometer for measurement, thus showing that the error of estimation is not large compared with the others, so that in general it is not important to estimate each plate twice, as is sometimes done.

The mean error of one photovisual magnitude, similarly determined, is about $\pm 0^m.05$, the difference in accuracy arising from the fact that the atmospheric extinction is about half as great as for photographic magnitudes, from the steeper gradation of the isochromatic plate (which gives for the same difference in brightness, a greater contrast in image intensity than a "photographic" plate*), and from the smaller range of wave length integrated as the "photovisual magnitude."

On a given plate, therefore, the apparent magnitudes may differ considerably from their true values. It is a common experience, and one that often distresses the beginner, that the intervals of brightness, and even the order of brightness of sequence stars, seem to differ from plate to plate. Sometimes the erring star can be shown to be variable, but more often the cause lies in the detailed differences of emulsion, or differences of instrument, color, or focus.

The magnitudes of individual sequence stars have a mean error of $0^m.06$. It is required to determine the mean error of the magnitude of the variable, determined from one plate by comparison with the sequence. This mean error is compounded of three errors: (1) mean error of magnitudes of sequence stars, referred to above; (2) error of estimation or measurement; (3) error in images of variable and of sequence stars, resulting from conditions of plate, instrument, and sky, on the particular plate involved. It is not necessary to separate (2) and (3); their combined magnitude can be determined by making estimates of non-variable stars by means of the sequence, and representing it by x'' we have, from direct observation:

$$x'' = 0^m.09.$$

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* This statement implies that the gradation of an isochromatic plate is greater than that of an ordinary photographic plate, and in general this is true for the plates commonly used for astronomical work. Even steeper is the gradation in the red-sensitive portion of the fast red plates usually employed. But it is not, of course, always true. A process plate is a blue plate of steeper gradation than the fast isochromatic plates generally used, and indeed, a large range in gradation may be secured by the appropriate choice and treatment of plates sensitized for most of the accessible spectral regions.

If we designate (1) by x', and the total mean error of one estimate of the variable as x, we have:

$$x^2 = x'^2 + x''^2$$

so that $x = 0^m.11$. Thus an estimate of a variable star by comparison with two sequence stars has a mean error of over a tenth of a magnitude, and for an ordinary focal plate it is usually unsafe to assume that an individual estimate is nearer than $0^m.15$ to the true magnitude of the star at the time. Therefore all photographic variable star work should be done with series of plates as extensive as possible, and ranges of less than a quarter of a magnitude cannot usually be safely studied unless special precautions are taken.

Out-of-focus plates, measured with a photometer, give a smaller mean error than estimates made on focal plates, by dint of reducing the error of estimation, and because they involve not two, but all the sequence stars. But even in this case the mean error of one measure of the variable can probably not be reduced beyond $0^m.08$.

The precision of "red magnitudes" (i.e., magnitudes obtained on red-sensitive plates through a red filter) is slightly less than that of yellow ones. This is because the quality of the images that can be obtained on red plates, at least with refracting telescopes, is not as good as on yellow plates, chiefly because photographic refractors are corrected for blue light, so that their red focus is poor, and partly because the fast red plates that have hitherto been used for stellar photography are of coarser grain than the yellow-sensitive plates usually employed in deriving photovisual magnitudes. None the less, the continuous progress in this field of plate sensitization and photometry renders the photo-red magnitudes a very important adjunct to the study of variable stars.

ix. *Selection and Establishment of Photographic and Photovisual Sequences.*—If there is a well determined sequence, covering the required interval of magnitude, very near to the variable, it may be used directly in estimating magnitudes. If it is near, but not near enough for direct use,* it may be employed as a secondary standard to determine a sequence immediately surrounding the variable. But in both cases it must be remembered that if the work is to be carried out with an instrument (or instruments) different from that by which the sequence was originally determined, the sequence magnitudes will inevitably differ in color system from the magnitudes to be derived for the variable.

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* It is always very important to have the variable and the comparison stars simultaneously in the field of view, so that the eyepiece of widest angle compatible with the necessary magnifying power should be used for the estimations.

So great are the difficulties introduced by using in one color system a sequence that has been derived in another, that it is desirable, *whenever possible,* to determine the magnitudes of comparison stars directly, with the instrument that is to be used in observing the variable. There are many methods of doing this; we shall describe one of the simplest, which we have found in practice to give results as good as those from any other method of equal speed.

A number of plates are exposed successively on the same night, under precisely the same conditions, and with precisely the same exposure, on the vicinity of the variable, and on the North Pole. The plates should be of the same emulsion, and of the same age and history; to insure this, they should all come from the same box. In addition, they should be developed simultaneously in the same developer. The exposures should be alternated: Pole, Field, Pole, Field, Pole, Field; the time being chosen so that the Field is always at the same altitude as the Pole, or higher.* The exposures must be such that the faintest sequence star required gives a measurable image, for extrapolated sequences are always to be avoided.

The plates may be measured visually with a graduated intermediary scale of images, or with a suitable photometer. The average scale measure for each star, derived from all pole plates of one series, is then plotted against the corresponding photographic magnitude for all except the stars whose designation is followed by "r" (red); the latter stars should, however, also be measured. A smooth curve is drawn through the plotted points; the curve will certainly not be linear, and may even show waves, but the points should be followed faithfully in the smooth curve, and the investigator should avoid prejudice by recalling that all photographic plates differ one from another. The magnitudes of the selected field stars are then determined by reading from the curve the magnitudes corresponding to their scale readings.

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* It is possible to photograph Field and Pole on the same plate; in this case the plates should be paired, with exposures in the order: (1) Pole, Pole, Field; (2) Field, Field, Pole. The two exposures on the same region serve the double purpose of helping to eliminate the effect of order of exposure, and of aiding in identifying two superimposed star fields. On the whole, however, the use of different plates for the successive exposures repays the extra expense, in observing speed and in convenience of measurement.

The magnitudes of the sequence stars, thus determined, must be corrected for differential extinction. The altitude of the field at mid-exposure being known, the appropriate corrections are taken from a table of extinctions, preferably one determined for the locality. Altitudes lower than the Pole should be avoided because for them the differential extinction rapidly becomes large. If an extinction correction is required for photovisual plates, a satisfactory approximation is obtained by halving the photographic corrections, in the absence of a direct determination.

Measures on six or eight plates, obtained on at least two different nights, should suffice to give reliable magnitudes for the sequence stars.

The color equation of the system of magnitudes given by the instrument used, with respect to the International System, is obtained by reading from the mean reduction curve, drawn for the other Pole stars, the magnitudes of the "r" stars of the Polar sequence. The color equation of the system being expressible in the form cI where I is the color index and c the color coefficient, we obtain:

$$cI_i = m_i - m_j$$

where m_i and m_j are the magnitudes of the "r" stars in the International System and the system under investigation, respectively.*

The procedure just outlined is only applicable in the northern hemisphere, and should only be used at stations north of latitude 40°. South of this limit, one of the Harvard Standard

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* This form of the relation assumes that the color coefficient is a linear function of the color index, which is not always so. In practice it may be well to use an empirically found relation between c and I (See Subsection 56, i).

Regions should be used to establish the scale, and south of the Equator this is not only desirable but unavoidable. Other things being equal, the Harvard Standard Regions at +15° and −15° (the C and D regions) are the most reliable (especially the C regions), and in nearly all latitudes where observatories are situated, they rise high enough in the sky to furnish satisfactory standards.

The number of comparison stars useful in a sequence differs with the type of variable and the taste of the observer. Small intervals of magnitude are a disadvantage, because they may be distorted by individual plate errors. For most purposes an interval of about four-tenths of a magnitude between successive sequence stars will be found satisfactory. Stars of small range require smaller intervals; stars of large range permit larger ones.

x. *Use of Photographic Standards.*—Be it supposed that a variable star is to be studied, and that we are provided with a nearby sequence of stars of graduated and known brightness. There are several radically similar ways of expressing the brightness of the variable in terms of the brightness of the sequence stars. The choice is a matter of individual taste. Like many kindred matters, the estimation of variables from photographs (or, indeed, visually) is largely a matter of knack or *flair.*

Some of the best estimators work rapidly. A novice is apt to think that the process is a difficult one, requiring thought and deliberation. But to work "on the toes" for a comparatively short time produces better results than making the same number of estimates with great deliberation, with its attendant boredom and fatigue. Long sessions of measurement may be greatly lightened by working in a condition of mental alertness and bodily relaxation, and by realizing when using an eyepiece, where the image is formed.*

Direct Estimation: Suppose the variable and its comparison stars to be simultaneously visible; the brightness of the variable may be directly estimated in magnitudes from a knowledge of the magnitudes of the comparison stars. Or it may be expressed on an empirical scale, relative to the comparison stars and afterwards computed—sometimes an advantage in postponing the determination of precise sequence magnitudes until it is certain that they will be needed. An accurate knowledge of magnitudes is not for example nearly so necessary for an R Coronae star as for an eclipsing star for which an orbit is to be computed.

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* Experience with a number of untrained observers who have to do eyepiece work on photographic plates suggests that most of them unconsciously focus their eyes on the place (near the end of their noses) where they suppose the image to be; and that eyestrain results. It is usually a relief to them to be told where the image is.

The magnitude of the variable may also be expressed in the "step method"—the observer estimates the number of "steps," or distinguishable grades of brightness, between each successive pair of comparison stars; estimates of the variable are then made in the form "*b*2*v*3*c*," indicating that the variable is two steps fainter than *b* and three steps brighter than *c*. When the magnitude interval between *b* and *c* is determined, the relation between steps and magnitudes (assumed linear) may be used to determine the corresponding brightness of the variable.

In practice it is most advantageous to equate the brightness of a suitably chosen comparison star to zero, and that of the other comparison stars to numbers representing their differences, in steps, from the fundamental comparison star. Then when estimating or measuring the variable, one records only the number of steps from this arbitrarily chosen zero. For example, the estimate given above (*b*2*v*3*c*) could, with the same precision but with greater economy of time, be written 3, if $c = 0$ (consequently $b = 5$), or -2 (if $b = 0$, $c = -5$). When there are several comparison stars, the system of adding the step intervals is obvious. An important advantage of the "step method" is that while a step has a definite numerical relationship to the magnitude scale, it can be adapted to the personal preferences of the measurer. Some astronomers use large steps (about two-tenths of a magnitude); some prefer small ones (about eight-hundredths). In favorable cases even a half-step can readily be estimated.

The nature of a step can best be learned from seeing an experienced observer at work. We may give a practical example of the formation of the first three steps. One looks at two stars, which seem to be of equal brightness, but on more intensive scrutiny one says: "No; *a* is brighter; yes, *a* is brighter." The difference of brightness may be taken as one step. If the second comparison shows that *a* is definitely brighter, the two stars being, however, of comparable intensity, we may say that *a* is two steps brighter than *b*. If they appear slightly different, even at the first glance, and if further scrutiny confirms this, then they may be separated by three steps.

It is not advisable to take comparison stars with differences of more than four or five steps. Nevertheless, if one has developed an art (and estimation of magnitudes is an art) of estimating over an interval of more than five steps, one can, in case of necessity, use stars separated by eight or ten steps, corresponding, with an experienced observer, to an interval of about $0^m.7$. Less experienced observers will at first use larger steps.

Another method, preferred by many observers, is to estimate the magnitude of the variable in tenths of the interval between successive sequence stars, reduction being carried out as for the step method. The two methods demand, respectively, the knack of estimating successive equal grades, and the knack of decimal subdivision.

Indirect Estimation: For a direct estimate, the determination of the brightness of the variable depends on the accuracy of the magnitudes and images of two comparison stars only. It is possible, though usually too lengthy, to use the whole sequence in estimating the variable. For this purpose the variable, and all the stars of the sequence, are measured with a suitable scale and photometer, and the measures for the stars of the sequence are plotted against their magnitudes. This method is too lengthy for use with one variable, but might be employed with profit when a number of variables are to be studied in one field, with the aid of one central sequence, so far from some of the variables that direct estimation is not possible.* It has the advantage of eliminating two troublesome sources of systematic error for direct estimation—an unconscious tendency to favor one of the sequence stars, and the danger of "decimal selection."* For most work, especially on single variables, it is best, if possible, to work by direct estimate (determining a sequence if necessary to resort to indirect estimation).

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* It is not safe to make comparisons for stars not visible at the same time in the field of the eyepiece. Sometimes, as with very bright variables, there are no suitable comparison stars nearby, and then it is usually necessary to resort to indirect estimation.

57. Discussion of Observations.—i. *Determination of Period.*—The first step in studying a variable star is to decide whether its changes in brightness are periodic. Often, as with long period variables observed over a considerable interval, the approximate period is at once obvious. In other cases the matter is less clear.

It is useful to know what type of variable we are dealing with, and this can often be determined, before the period is known, from the frequency distribution of the observed magnitudes, or the rate of change in brightness. An eclipsing star is easily recognized by the small fraction of "faint" observations, an SS Cygni star by the small fraction of "bright" ones.[3] A brightening of the order of a magnitude in an hour spells a cluster type star or a nova.

The determination of periods from observations of brightness made at known times is difficult to describe; in many ways it is an art, acquired by practice, and varying with the peculiarities of individual stars and the distributions of observations. A few general principles may, however, be laid down.

The times at which a definite phase of the variation occurs (such as the minimum of an eclipsing star or the maximum of a cluster-type star) form the basis of the preliminary search for a period. A taking of first, second, and sometimes higher differences will often reveal intervals with an obvious common denominator, which is some multiple of the period. When the least common denominator of all the observed intervals between similar phases has been found, it is used as a trial period, to find what submultiple of it is satisfied not only by the magnitudes at one phase, but by all the observations.

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* "Decimal selection" is the tendency to select some tenths rather than others; most estimators, unless especially on their guard, avoid .9 and .1 and favor .0 and .5. If affecting direct estimates from sequence stars, decimal selection will give a "staircase" form to the light curve but if operating on arbitrary scale divisions it should have no systematic effect on the magnitudes.

[3] *See* Opik, H.C. 393, 1933.

The observed intervals, and differences between intervals from one specified phase to the next observed occurrence of that phase (recognized by the maximum or minimum brightness), may be analyzed in the following manner. If t is the observed time of the selected phase, P the period, and n an integer, we have:

$$Phase = t - nP$$

$$\text{or: } Phase/P = t/P - n$$

Consider a given phase F_x. For one observation at that phase, designated by y, we have:

$$F_x/P = t_y/P - n_y$$

and for another observation, designated by z, at the same phase F_x:

$$F_x/P = t_z/P - n_z$$

Subtracting,

$$n_y - n_z = 1/P\ (t_y - t_z)$$

The quantity $(n_y - n_z)$ is an integer, since n_y and n_z are integers. The quantity $(t_y - t_z)$ is the interval between successive observations at the same phase F_x. Therefore, since $1/P(t_y - t_z)$ must be an integer, the quantity $1/P$ is the factor by which all observed values of $(t_y - t_z)$ must be multiplied to give integral values. When this condition is fulfilled the reciprocal of the period has been determined. All the calculation and adjustment is made with this reciprocal, rather than with the period itself.

In illustration of the application of this method, Table XII, I gives, in successive columns, the times of observed minimum for the eclipsing star, U Gruis, the first differences, and final values of $1/P\ (t_y - t_z)$ obtained after several trials in determining the period. It will be seen that all values in the last column are nearly integral.

The knack of the computer is called out in making small adjustments to the determined period, in order to represent all the observations as well as possible. In doing this, the observations are weighted, it being remembered that the time of an observation is in general more accurately known than the brightness.

TABLE XII, I

DETERMINATION OF PERIOD OF U GRUIS ($P=1^d.88048$)

Times of Minima J.D.	Differences d	$1/P\ (t_y - t_z)$ $(1/P=0.531779\ d^{-1})$
2411202.776		
	329.073	174.99
11531.849		
	2220.899	1181.03
13752.748		
	1446.049	768.98
15198.797		
	142.740	75.91
15341.537		
	632.096	336.14
15973.633		
	406.045	215.93
16379.678		
	16.992	9.04
16396.670		
	315.916	168.00
16712.586		
	1083.165	576.00
17795.751		
	691.995	367.99
18487.746		
	112.791	59.98
18600.537		
	2138.166	1137.03
20738.703		
	16.926	9.00
20755.629		
	280.171	148.99
21035.800		
	2957.963	1572.98
23993.763		
	97.764	51.99
24091.527		
	199.347	106.01
24290.874		
	361.019	191.98
24651.893		
	131.668	70.02
24783.561		
	14.961	6.89
24798.522		
	16.998	9.04
24815.520		
	712.724	379.01
25528.244		
	1100.117	585.02
26628.361		

ii. *Erroneous Periods.*—It is impossible to observe stars continuously from any observatory at present in use, and this restriction causes difficulties in the determination of periods. Observations of any one star are necessarily made at approximate daily intervals; some work (in order to avoid the light of the moon, or perhaps because of observing schedules) is made approximately at monthly intervals; and a yearly period is also imposed on stellar observations. Thus the study of variable stars may be compared to the stroboscopic study of running machinery. A spurious period, depending on the period of the intermittent illumination as well as on that of the machine, is imposed on the operations, and in certain circumstances the machine may be made to appear to run backwards.

The theory of the spurious periods thus imposed on variable stars is discussed by Hagen; here the matter will be briefly summarized, generalized, and illustrated. If there are observations of a variable star made at different times, the star can be said to be periodic if successive subtractions of a certain constant interval (the period) leave a number of remainders, smaller than the period (the phases), which, when plotted against the corresponding brightnesses, give a consistent and continuous change in brightness, within the accuracy of the observations. Any interval which arranges the phases in regular order, as judged by the progression of brightness, will thus appear as a possible period; and for many groups of observations there are several such possible periods.

Hagen discusses the case of three alternative periods. The representation of observations made at intervals of exactly a day by three periods is illustrated in Figure XII, 1. Let the three periods be P, p_1 and p_2, and let the phases of a particular point X of the light curve, corresponding to the three periods, be F, f_1 and f_2. Since phase is defined as $t/$ (period) where t is the interval from a specified point in the light curve $F = t/P$. The two smaller periods are, one rather larger than a day, and one rather smaller; if p_1 is the greater, we have from the definition of phase:

$$f_1 = t(1/p_1 - 1)$$
$$f_2 = t(1 - 1/p_2)$$

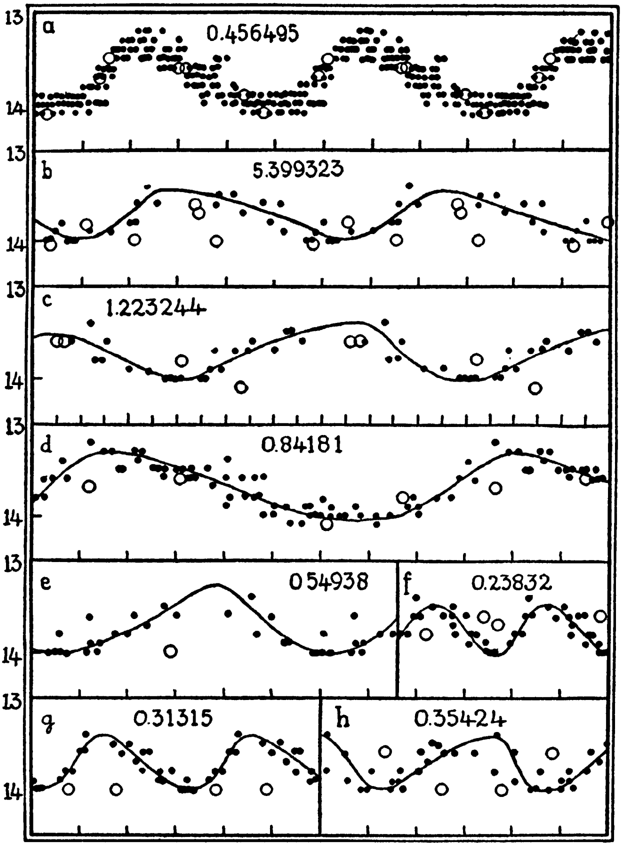

Figure XII, 1.—Observations of the cluster type variable QV Centauri, discussed with the correct period (a) and with seven spurious periods, related as follows (for notation, see text):

Figure	Period	n	Figure	Period	n
a	p_2 (true period)	2	e	p_1	2
b	P	. .	f	p_2	4
c	p_1	1	g	p_2	3
d	p_2	1	h	p_1	3

It will be noted the light curve "runs backwards" in Figures c, e, and h. The periods (days) are given in the figures.

Dots represent individual photographic observations. Circles represent observations of large hour angle. Abscissae are time: intervals of $0.^d1$ are indicated by short vertical lines in all figures except b, where the corresponding interval is one day. Ordinates are photographic magnitudes.

The observations and discussion are by Miss Frances Wright, with whose kind permission the figure is reproduced.

Hence we have the relationship given by Hagen:

$$\begin{aligned}
F &= -f_1;\ 1/p_1 + 1/P = 1;\ p_1 = P/(P+1);\ P = p_1/(p_1-1)\\
F &= +f_2;\ 1/p_2 - 1/P = 1;\ p_2 = P/(P-1);\ P = p_2/(1-p_2)\\
f_1 &= -f_2;\ 1/p_1 + 1/p_2 = 2;\ p_1 = p_2/(2p_2-1);\ p_2 = p_1\ (2p_1-1)
\end{aligned}$$

The more general form for the relation given in the last two lines of the last column $P = p/(\mp p \pm 1)$ is: $P = p/(\mp np \pm 1)$ where n can have any integral value. The possible periods are grouped in pairs on either side of simple fractions of one day. The general form of Hagen's table is then:

$$\begin{aligned}
F &= -f_1;\ 1/p_1 + 1/P = n;\ np_1 = P/(P-1);\ P = p_1/(np_1-1)\\
F &= +f_2;\ 1/p_2 - 1/P = n;\ p_2 = P/(np+1);\ P = p_2/(1-np_2)\\
f_1 &= -f_2;\ 1/p_1 + 1/p_2 = 2n;\ p_1 = p_2/(2np_2-1);\ p_2 = p_1/(2np_1-1)
\end{aligned}$$

The sidereal day is the interval most likely to be impressed upon the observations, because observations are most apt to be made when the object is near to the meridian.

There is thus an infinite number of spurious periods associated with every true period, and if all observations are made exactly on the meridian, the period is not made more certain by increasing the number of observations. In order to distinguish between the possible periods that can be used to represent a series of observations, it is necessary to have some measures made outside the usual interval—for example, if the period of the observations is the sidereal day, some observations should be made far from the meridian, and discussed separately; it is these observations alone that will discriminate between the possible related periods. The best method of fulfilling this condition is to have several observing stations separated in longitude. The spurious period may be associated with the sidereal day, or the solar day, the lunar month, or even the year.

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